N63-22161

AIR PRODUCTS AND CHEMICALS, INC.

ALLENTOWN, PENNSYLVANIA

Pa.

REPORT

OF

DEVELOPMENTAL TESTS

FOR THE

LIQUID HYDROGEN SERVICING SYSTEMS,

COMPLEX 37B, SATURN C-1

CAPE CANAVERAL, FLORIDA

Prepared For:

National Aeronautics and Space Administration

George C. Marshall Space Flight Center

Huntsville, Alabama

Prepared By:

R. E. Sotak

28 February 1962

Contract No. NAS8-1546

APCI Project No. 00-1-3140

104p

TABLE OF CONTENTS

I Introduction

Under NASA Contract No. NAS8-1546 a liquid hydrogen servicing system was designed for launch complex 37B, Saturn C-1 at the Atlantic Missile Range. The first part of this contract was used to develop criteria from which the system would be designed. During this criteria development phase it became clear, that certain components of the system should be tested prior to field installation at the Atlantic Missle Range to prove performance, verify design concepts and in general save time for the overall program.

Flowsheet D10462600 indicates the components used in the system. Of these components the cold hydrogen gas pump which is used to generate low temperature liquid hydrogen in the subcooler was a complete new development. In other words, a pump of this type had not been built previously, either by industry or the government. All other components could be designed and constructed with a much greater degree of confidence, because considerable previous experience was available. In addition to the cold hydrogen gas pump, the following components were selected to undergo testing prior to installation in the hydrogen servicing system.

(a) A section consisting of one third of the vaporization coil to be used. Testing of this section was considered necessary, because data available were scant and in general were obtained with much smaller scale equipment.

(b) The complete hydrogen vent system from the umbilical tower. Testing was necessary in this case because prior experience with a burn pit as contemplated was not available. Also, the pressure drop allowed by the stage contractor was so low, that verification was deemed necessary.

(c) The liquid hydrogen subcooler was tested to verify the design calculations and to make sure that the stage contractor's requirements with regard to liquid temperature would be met.

The tests were carried out at Air Force Plant 74 in West Palm Beach, Florida. Air Products and Chemicals, Inc. is the operator of the plant which fact simplified scheduling of the test program. Large quantities of liquid hydrogen are available, of course, which allowed testing to be accomplished under conditions similar to final use at the Atlantic Missile Range.

II Summary of Test Data

In order to provide the essential data of this test report to a reader, who has little time available, a short summary describes the important results achieved in the test program.

(a) Vaporization Coil

Test results achieved with one third of the vaporization coil to be used with the liquid hydrogen storage tank indicate, that at a flowrate of 2200 to 2300 gpm to the vehicle a pressure of 42 psig in the storage tank can be maintained. The design of the system requires a flowrate of 2000 gpm while maintaining the storage tank pressure at 45 psig. The pressure drop in the vaporization coil also is low enough to allow maintenance of a constant pressure of 45 psig in the storage tank to a very low liquid level.

There is no limitation with regard to time on the vaporization coil. In other words, pressure can be maintained in the storage tank for long periods of time.

(b) Vent System for the Vehicle

At the design flowrate of 2000 lbs per hour the pressure drop in the complete vent system will be less than .25 psig. At a flowrate of 3000 lbs per hour the pressure drop will be approximately .25 psig. It is obvious that a large amount of gas can be handled with the system, which increases the inherent safety of the vehicle system. The insulation provided for the first 100 ft maintains the vent line at a temperature high enough to prevent formation of liquid air and fog. The ignition system consists of a hot wire, which requires 250 watts of electric power to ignite hydrogen gas under a wide variety of weather conditions. The ignition system operated satisfactorily with wind velocities up to 22 miles per hour and flowrates up to 6000 lbs per hour. The system also operated satisfactorily during a rain storm.

Temperature profiles were taken above and around the burn pit. The tests showed, that a very substantial amount of the heat of the flame is dissipated in the water and that temperatures do not exceed 300^{o}F at distances of 20 feet from the edge of the burn pit in the downwind direction. Equipment in the launch area will be perfectly safe with any conceivable flowrate handled by the vent system.

(c) Liquid Hydrogen Subcooler

Under all operating conditions of the liquid hydrogen servicing system liquid hydrogen passes through the subcooler on its way to the vehicle. The pressure drop experienced in the subcooler is 2.25 psig for a flowrate of 2000 gpm.

Heat transfer in the subcooler between the cooling liquid hydrogen and the stream to be cooled is adequate for all operating conditions of the liquid hydrogen servicing system. It will be possible to satisfy the stage contractor's requirements during the replenish period for both high and low flowrates. Satisfactory performance of the subcooler depends on the operation of the cold gas vacuum pump. Without the vacuum pump it is impossible to generate the low temperature required for removal of the heat from the liquid stream flowing to the vehicle.

(d) Cold Gas Vacuum Pump

The cold gas vacuum pump was tested together with the subcooler. Independent data are therefore not available for the pump.

The pump has been operated for approximately 100 hours, of which 50 hours in hydrogen gas service and 50 hours in nitrogen gas service. The pump performed satisfactorily during the full 100 hours without apparent deterioration in performance. Blank off pressure, that is obtainable suction pressure without flow through the pump, was 1 psia on the cold hydrogen gas. This indicates quite satisfactory sealing characteristics of the valves. The pump was operated at two speeds, 412 and 512 rpm and the design criteria, 98.6 acfm at -426°F and 8.5 psia, were fulfilled at the low speed. Inspection of the unit after the test program was completed showed it to be in excellent condition.

III Storage Tank Pressurization Coil

Introduction

This report covers the experiments performed on one of three identical sections of the pressurization coil which will be used for pressurization of the 125,000 gallon liquid hydrogen tank of the hydrogen servicing system for the Saturn Space Vehicle on complex 37.

The purpose of these experiments was to obtain data to,

(1) Verify the design calculations of the coil.

(2) Determine the amount of pressure surge due to liquid residual in the coil.

(3) Verify the calculated pressure drop across the coil.

Pressurization Coil Design

Figure 1 shows a section of the vaporization coil to be used for pressurization of the 125,000 gallon storage tank. A total of three identical sections piped in parallel will be used. A single section of coil consists of 4-1/8" O.D. copper tubing. To limit physical size of the coil 5 equal pieces of approximately 20 ft lengths are connected through 180° bends to make one continuous length of copper pipe. Liquid is admitted through a header, and cold gas is collected at the other end by a second header. The coils are placed horizontally on a simple support.

Test Apparatus

Figure 2 indicates the process flowsheet of the test setup. Liquid hydrogen flows from dewar "D" through an orifice type flow indicator into the pressurization coil test section. The line between dewar "D" and the test section is insulated and little or no vaporization takes place in this line. The vaporized liquid flows out of the test section into a stack. Pressure drop across the coil is measured by a pressure differential indicator PDI-1. Accurate measurement of the flow through the test section is measured by the decrease in weight of dewar "D". A print out circuit indicates the weight of dewar "D" every 10 seconds and integration yields total flow over a period of time and flowrates at any one time.

Temperature measurements are made at points one through seven. Hydrogen vapor pressure thermometers are used at points one and two, and copper-constantan thermocouples at points three through seven. A twelve point temperature recorder was used to obtain a continuous record of various temperatures in and on the coil. Pressure control in the test section was exercised by maintaining a constant pressure over the liquid in dewar "D" and controlling flowrate through valve V2. Valve V1 is opened wide during the tests and only a small amount of pressure drop exists in the insulated liquid supply line to the coils.

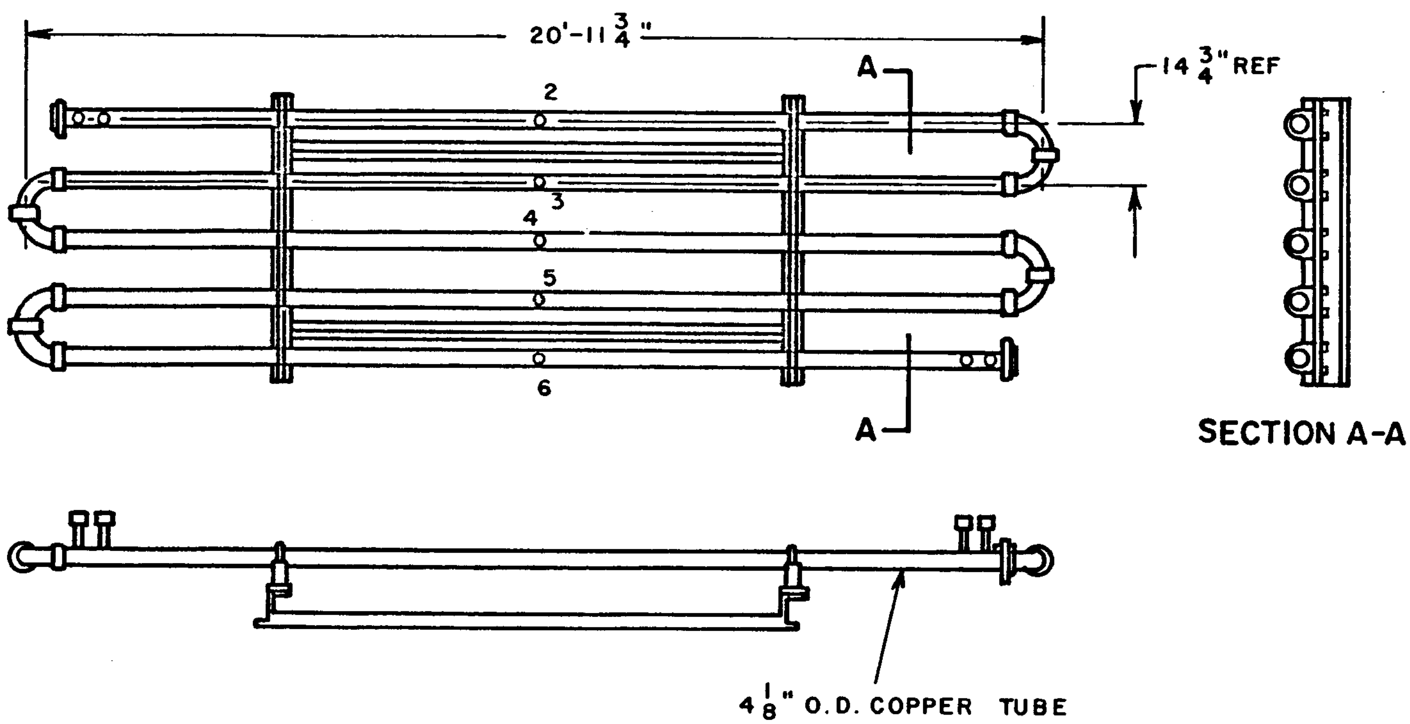


FIGURE I

SECTION OF PRESSURIZATION COIL

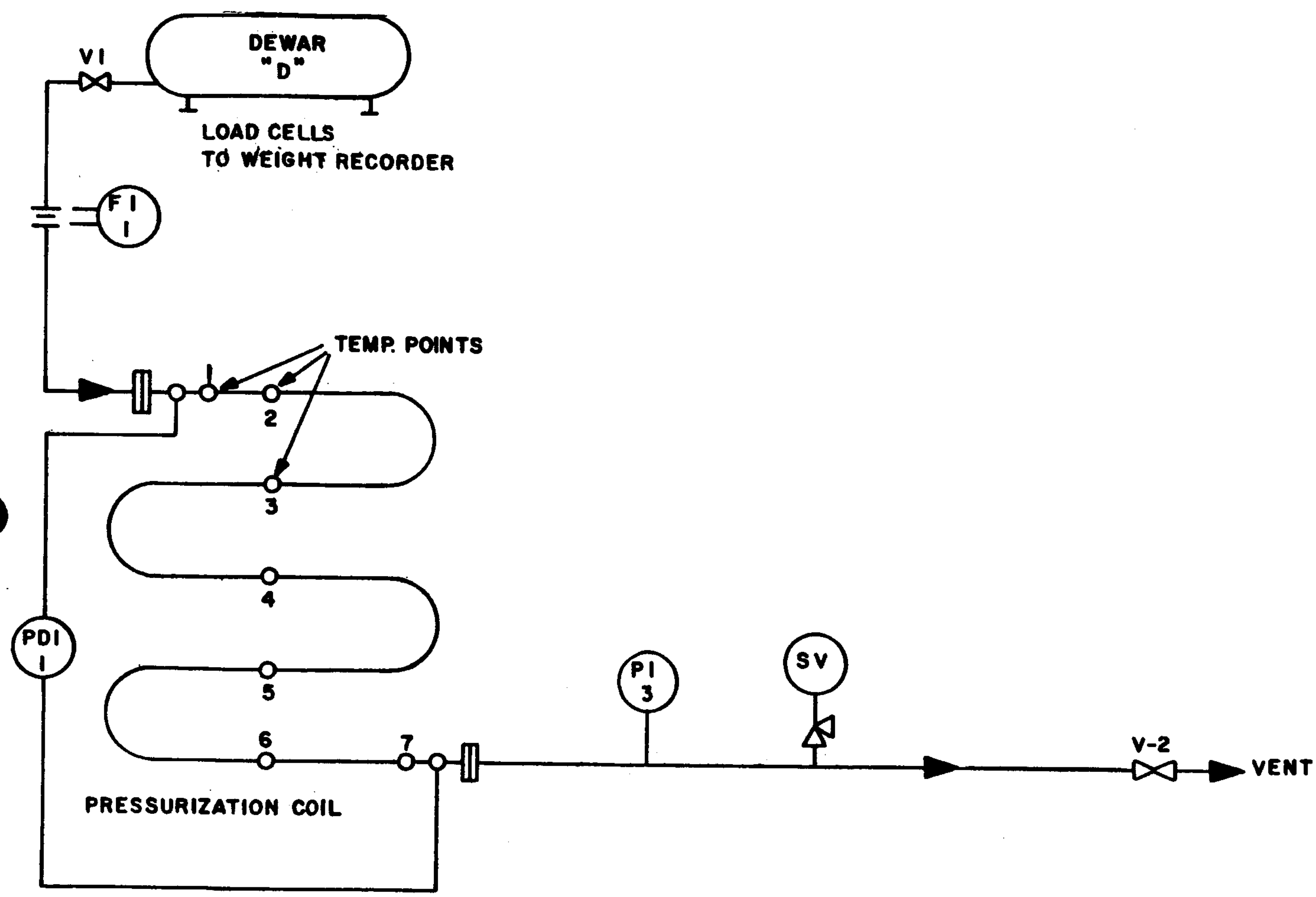


FIGURE 2
PRESSURIZATION COIL TEST
FLOWSHEET

Discussion of Results

To provide a continuous driving force for transfer of liquid from the storage tank to the vehicle, the vaporization coil is required to generate a volume of gas equal to the volume of liquid which is being displaced from the storage tank at the pressure which is maintained in the storage tank.

In order to predict the liquid flowrate, which can be maintained at a constant pressure in the storage tank, the test results of the coil have to be translated into volume of gas generated by the pressurization coil. By determining the temperature and pressure of the gas leaving the coil and number of pounds flowing through the coil make it possible to calculate the actual volume of gas.

Because of so-called liquid hold up in the pressurization coil, pressure surges will occur when liquid flowrates out of the 125,000 gallon storage tank are changed. In practice this occurs during the period of replenishing of the vehicle when flowrates will oscillate between 20 and 500 gpm. An attempt was made to measure the amount of liquid present in the coil. However, the use of hand valves in the test system made it impossible to close and open the proper valves simultaneously and the liquid hold up remaining in the coil could not be measured accurately.

Pressure drop across the coil is very important. The driving force to force liquid through the pressurization coil is furnished by liquid head in the tank. In the case of liquid hydrogen 33 ft of liquid head represents only one psig pressure. Obviously, the pressure drop in the coil has to be low in order to be able to generate enough gas even at low liquid levels in the tank.

The results of the tests are maintained in figures 3, 4 and 5. Figure 3 shows the hydrogen flowrate through the test section of the coil as a function of pressure drop across this test section. A pressure drop of 1.2 inches of H_2O allows a flow of 800 lbs of hydrogen through the coil. One and one half foot of liquid hydrogen level in the 125,000 gallon storage tank provides the head equivalent to 1.2 inches of H_2O.

Figure 4 shows the temperature of the gas at the outlet of the coil as a function of the flowrate through the test section.

Figure 5 shows the calculated effect of the performance of the test section of the coil on the 125,000 gallon storage tank. The figure was composed after the results of figures 4 and 5 were translated into volume of gas leaving the test section of the vaporization coil. Since tests were carried out at two pressure levels volume of gas leaving the test section was calculated at two pressure levels. The ordinate of figure 5 indicates the volume of gas generated by the test section. Under equilibrium conditions this volume of gas is the same as the volume of liquid leaving the storage tank on its way to the vehicle. The abscissa of figure 5 indicates the amount of liquid vaporized in the test section. Since the actual installation

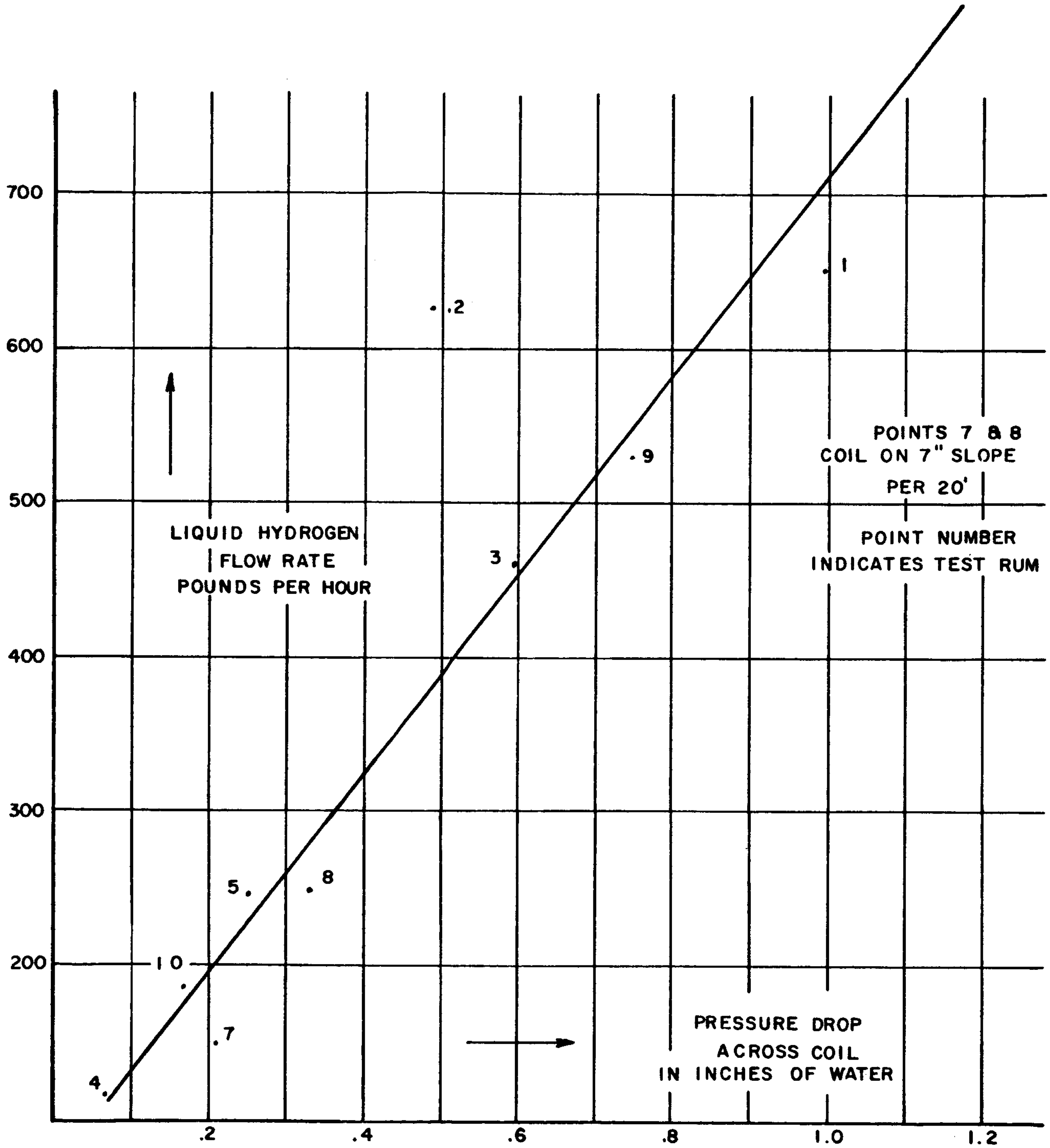


FIGURE 3

HYDROGEN FLOW RATE THROUGH COIL VS.
PRESSURE DROP ACROSS COIL

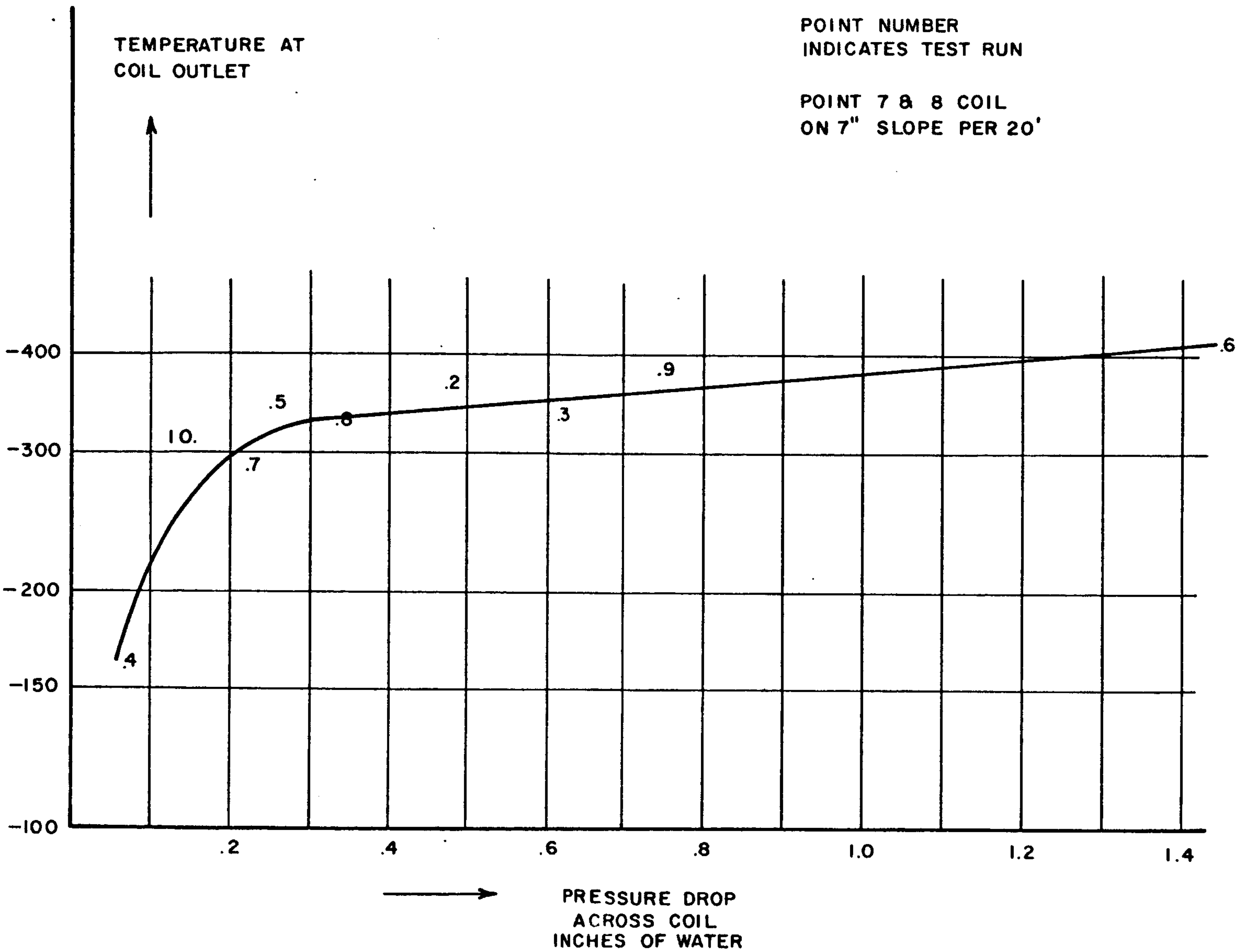


FIGURE 4

HYDROGEN TEMPERATURE AT COIL OUTLET
VS.
PRESSURE DROP ACROSS COIL

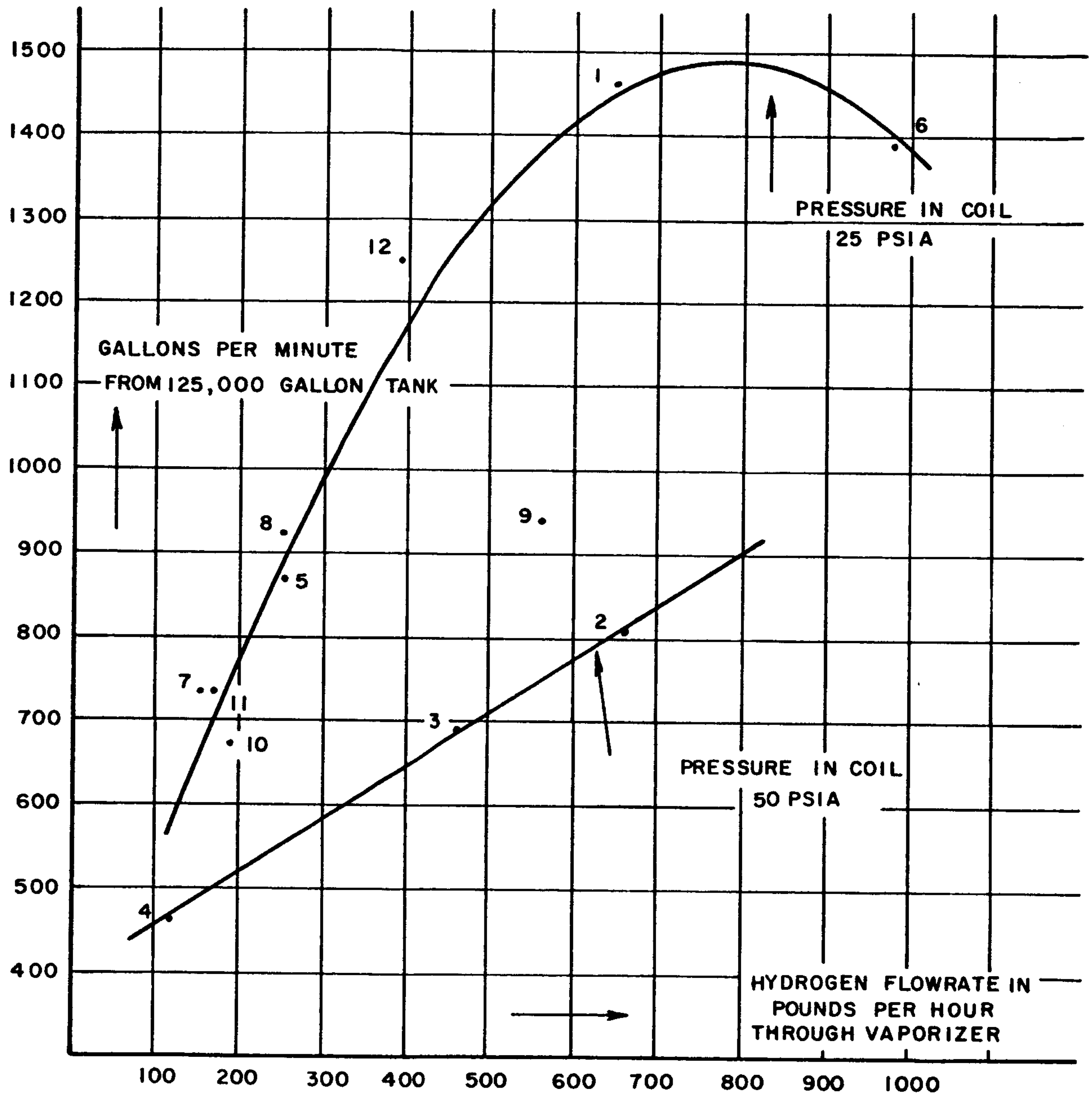


FIGURE 5

HYDROGEN FLOW RATE OUT OF TANK VS HYDROGEN FLOWRATE THROUGH VAPORIZER at the Atlantic Missile Range will have three identical test sections in parallel, the numbers of figure 5 will have to be multiplied by three to represent actual flow conditions. As an example; at a constant tank pressure of 35 psig, a flow rate of 2700 gallons per minute can be maintained by vaporizing 2400 lbs per hour of liquid hydrogen. For every gallon of liquid transferred from the tank, .025 gallons are vaporized to maintain a constant pressure of 35 psig.

It should be noted that the measurement of the gas temperature at the outlet of the test section in the temperature range of -400°F is not extremely accurate. A variation of $\pm$ 10°F in the gas temperature yields a variation of approximately $\mp$ 15% in the volume flow of liquid from the storage tank.

The formation of frost on the test section is a function of flowrate through the section and ambient conditions. At moderate and high flowrates through the test section (500 lbs/hr and higher) liquid air is formed over the full length of the test section and the frost cover consists of a slushy wet mass of approximately 1/8" thickness. At lower flowrates a dry frost cover develops near the exit of the test section. At all times a considerable part of the surface of the test section remains relatively clean, and deterioration of performance of the coil will not take place.

During the initial cooldown of the coil considerable temperature gradients are developed. However, stress problems do not exist and bending or traveling of the test section did not occur to any noticeable degree.

Heat Transfer Coefficients

The results of the tests do not bear out the calculations made originally. The calculations were carried out with the assumption, that after a certain number of feet the liquid is all vaporized and that from there on only gas exists.

The actual case is different. For instance, temperature measurements made around the pipe (bottom, middle and top) for a single cross-section indicate that a very significant difference can be maintained. Tests 12 and 13 show a difference of 30°F and 26°F respectively between top and bottom of the pipe at the mid-point of the pipe. In both cases the bottom of the pipe is cold enough to liquefy air and this is observed.

Apparently liquid hydrogen is present over a long stretch of pipe with the bulk of the cross-section filled with gas. Heat transfer, therefore, takes place between wall and hydrogen gas, wall and hydrogen liquid and hydrogen gas and liquid. This explains why the temperature of the gas changes so little over the full length of the vaporization coil at fairly high flowrates. At low flowrates of approximately 100 lbs per hour we can be sure that no liquid exists at the end of the pipe and the gas warms up considerably.

The above does not mean that the coil will not perform satisfactorily. Pressure drop will determine this primarily. The pressure drop with approximately 1000 lbs. of hydrogen per hour passing through is only 1.44 inches of water and much more can be passed with the liquid head available in the 125,000 gallon storage tank.

Sloping the coil slightly (seven inches in 20 feet) showed a marked difference in outside appearance. Liquid air was dripping very heavily off the low point, indicating a sizable accumulation of liquid hydrogen inside the elbow. The first temperature point beyond the elbow indicated a much lower than usual temperature, indicating carry over of liquid hydrogen with the gas from the elbow.

Appendix 2 contains illustrations of the pressurization coil prior to and under test conditions. Different types of frost formation at various flowrates and ambient conditions are brought out in the illustrations.

Conclusion

The tests carried out indicate that a vaporization coil consisting of three parallel identical sections of the type tested will provide sufficient vaporization to maintain a flow of 2000 gpm of liquid hydrogen from the 125,000 gallon storage tank at a pressure of 42 psig in the tank. Lower flows during the replenishing period of the S-IV vehicle will be maintained easily. During the period of replenishment the vaporized liquid will warm to a considerably higher temperature in the coil. Reference to figure 5 indicates that the amount of liquid vaporized in the coil will be approximately 200 lbs/hr to maintain a flowrate of 500 gpm from the storage tank.

Installation of the vaporization coil is not critical. The coil should be installed nearly level, but special precautions for leveling do not have to be provided.

APPENDIX I

DATA SUMMARY

PRESSURIZATION COIL

APPENDIX I

DATA SUMMARY

Test Run		1	2	3	4	5
Date		9/5/61	9/7/61	9/12/61	9/12/61	9/12/61
Relative Humidity %		54	64	64	59	64
Wind Velocity MPH		ENE 15	ENE 17	ENE 12	ENE 12	ENE 15
Ambient Temperature ^{o}F		92	90	86	96	94
Coil Pressure PSIG		10	32.5	35	35	10
H_2 Flow Rate (lbs/hr)		652	630	460	115	248
Coil Pressure Drop (Inches of Water)		1.0	0.49	0.6	0.06	0.25
Liquid Holdup in Coil (lbs)		1.34	-	-	-	0.517
H_2 Temperature at Equilibrium Conditions ^{o}F						
Point	1	420.8	416.6	416	408.8	419.2
(All Temperatures Minus)	2					
	3	385	390	352	295	345
	4	382	370	348	250	342
	5	379	368	346	210	340
	6	377	362	342	172	338
	7	375	360	340	154	330
Outside Wall Temperatures At Equilibrium Conditions ^{o}F						
Point	1	396	390	360	312	338
(All Temperatures Minus)	2	Off Chart	360	310	309	319
	3		340	-	246	-
	4	Off Chart	-	-	191	-
	5	Off Chart	-	305	-	-
	6	Off Chart	-	300	117	299
	7	326	-	300	96	291

DATA SUMMARY - Continued

Test Run		6	7	8	9	10
Date		9/12/61	9/14/61	9/14/61	9/19/61	9/19/61
Relative Humidity %		60	59	42	67	62
Wind Velocity MPH		NE 13	S 10	WSW 12	N 7	NE 7
Ambient Temperature °F		86	98	98	86	99
Coil Pressure PSIG		10	10	10	13.5	13.5
H_2 Flow Rate (lbs/hr)		984	150	250	530	186
Coil Pressure Drop (Inches of Water)		1.44	0.21	0.33	0.75	0.167
Liquid Holdup in Coil (lbs)		-	.533	1.14	-	-
H_2 Temperature at Equilibrium Conditions °F						
Point	1	420.5	411.3	419.7	418 to 419	410 to 418
(All Temperature Minus)	2	420.2	408.6	408.8	416-418	408-412
	2A	-	-	-	406-408	400-412
	3	-	353	362	380	333
	4	-	336	345	367	328
	5	-	316	332	380	315
	6	-	293	329	378	-
	7	402	282	322	375	308
Outside Wall Temperatures At Equilibrium Conditions °F						
Point	1	-	333	348	380	305
(All Temperatures Minus)	2	-	-	-	-	-
	3	-	320	340	-	-
	4	-	297	317	336	286
	5	-	262	-	-	280
	6	-	254	296	-	270
	7	-	242	284	330	-

DATA SUMMARY - Continued

		11	12	13
Test Run		11	12	13
Date		10/12/61	10/12/61	10/12/61
Relative Humidity %		62	71	71
Wind Velocity MPH		E 10	E 12	E 15-20
Ambient Temperature ^{o}F		106	91	82
Coil Pressure PSIG		10-15	10-16	10-15
H_2 Flow Rate (lbs/hr)		170	390	710
Coil Pressure Drop (Inches of Water)		.142	.43	1.0
Liquid Holdup in Coil (lbs)		DID NOT DETERMINE		
H_2 Temperature at Equilibrium Conditions ^{o}F				
Point	1	408.1	418.4	418.4
(All Temperature Minus)	2	409 -	410-418 400-418	415.2
	3	312	336	Below - $340^{o}F$
	4	324	335	Below - $340^{o}F$
	5	314	330	Below - $340^{o}F$
	6	291	323	Below - $340^{o}F$
	7	292	336	Below - $340^{o}F$
Outside Wall Temperatures At Equilibrium Conditions ^{o}F				
Point	1	335	345	-
(All Temperatures Minus)	2	283	324	-
	3	290	316	324
	4	286	307	-
	5	263	304	-
	6	260	311	-
	7	248	311	-

DATA SUMMARY - Continued

Outside Wall Temperatures Top and Bottom of Pipe

Point	3	Top	276	298	312
		Bottom	290	324	342
	4	Top	270	295	310
		Bottom	285	323	340

APPENDIX 2

ILLUSTRATION SUMMARY

PRESSURIZATION COIL

APPENDIX 2

ILLUSTRATION SUMMARY

PRESSURIZATION COIL

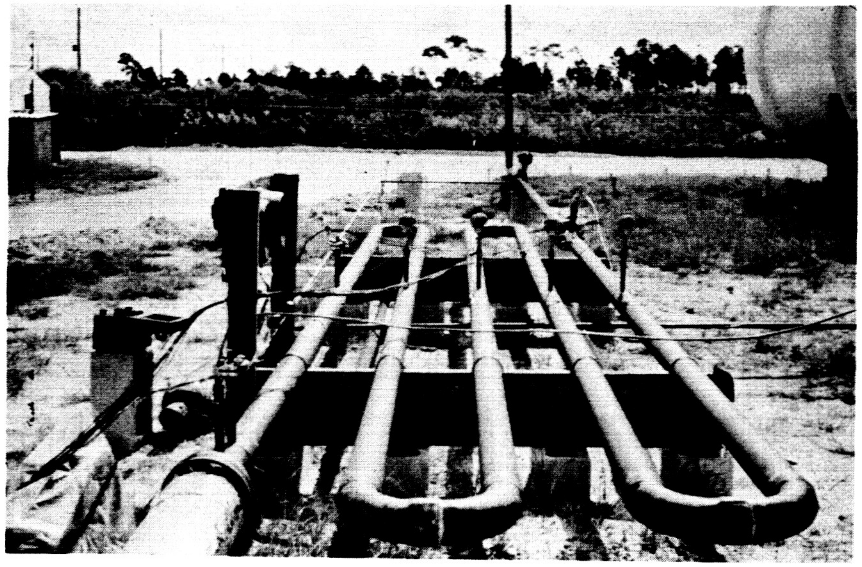


ILLUSTRATION 1

PRESSURIZATION COIL AT AIR PRODUCTS AND CHEMICALS, INC.

WEST PALM BEACH, FLORIDA TEST SITE

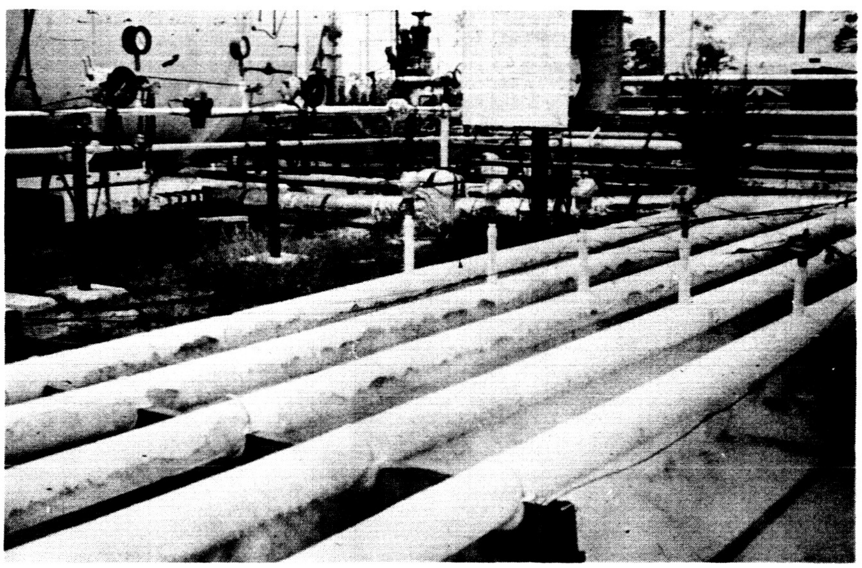


ILLUSTRATION 2

TYPICAL FROST FORMATION AT VERY LOW HYDROGEN FLOWRATES

APPENDIX 2

ILLUSTRATION SUMMARY

PRESSURIZATION COIL

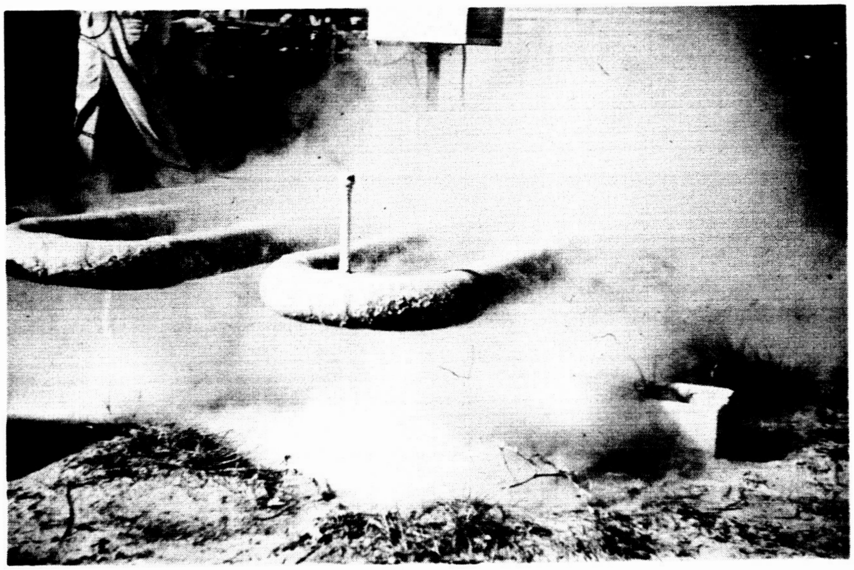


ILLUSTRATION 3

LIQUID AIR CONDENSATION AT VERY HIGH HYDROGEN FLOWRATES

NOTE CLEAN APPEARANCE OF COIL

ILLUSTRATION 4

OVERALL VIEW OF PRESSURIZATION

COIL AT LOW FLOWRATES AND VERY LITTLE WIND

APPENDIX 2

ILLUSTRATION SUMMARY

PRESSURIZATION COIL

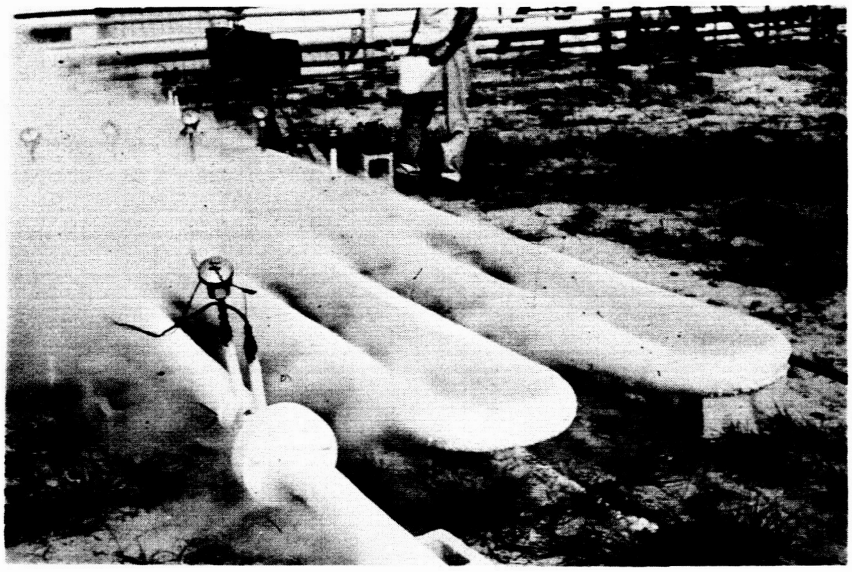


ILLUSTRATION 5

INTERMEDIATE FLOWRATE AND WIND OF 5 MPH.

LIQUID AIR FORMATION ON THE FIRST

ELBOW AND HEAVY FROST ON THE SECOND

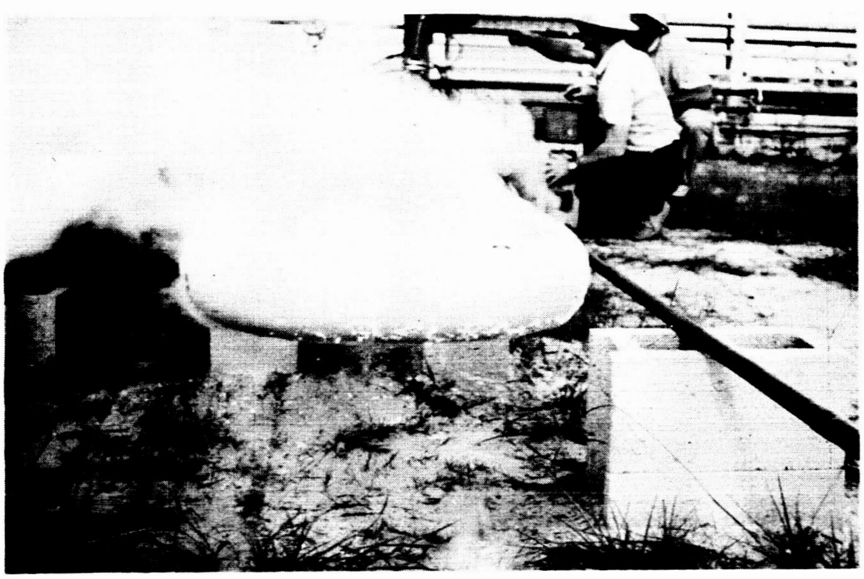


ILLUSTRATION 6

LIQUID AIR DRIPPING PROFUSELY FROM ELBOW

IV Launch Area Vent System

Introduction

This report covers the experiments performed on the full scale vent system and burn pit which will be used as part of the hydrogen loading system for the Saturn Space Vehicle on Complex 37.

The purpose of these experiments was to obtain data to:

(1) Verify the insulative qualities, against liquid air formation, of the lined pipe used in the vertical run of the vent system piping on the umbilical tower.

(2) Confirm the unrestrictive pressure drop through the vent and burn pit system.

(3) Observe expansion bellows under normal cold operating conditions.

(4) Determine the temperature profile of the hydrogen in the system and the corresponding wall temperature at points along the entire length of the line.

(5) Optimize ignition system type, location, and performance.

(6) Confirm burn pit water flow distribution and requirements.

(7) Determine flame patterns with respect to wind in form of temperature profiles and photography.

(8) Verify proper hydrogen dispersion in burn pit area.

Vent System Used for Test

Figure 6 shows a plot plan of the vent system as set up for the test. The full length of vent pipe as used at complex 37 was used during the test. For obvious reasons the vertical section on the umbilical tower was layed out horizontally. A full scale model of the burn pond as designed for complex 37 was used for the test. The hydrogen gas which under actual conditions will come from the vehicle, was generated in the vaporization coil discussed under section III of this report. This placed in some respects a more severe requirement on the vent system. For instance, insulation of the first 150 feet of vent line, representing the vertical section on the umbilical tower, was subjected to more severe duty. On the other hand, pressure drop measurements at high flowrates tend to be slightly optimistic, since the gas is maintained at a somewhat lower temperature throughout the vent line.

Figure 7 indicates a cross section of the insulated part of the vent line. A total of 150 feet of vent line was insulated in this manner. Two variations were employed as follows:

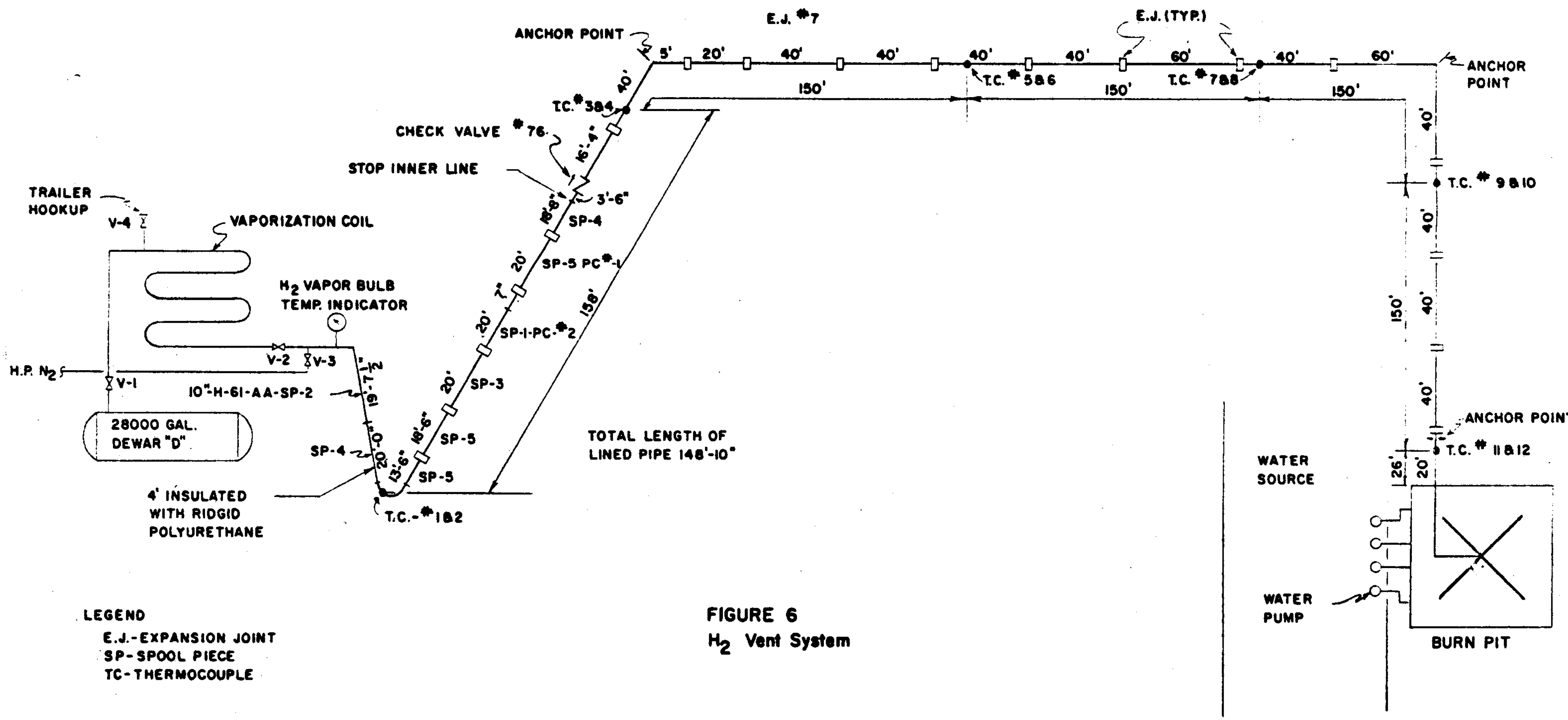


FIGURE 6
H_2 Vent System

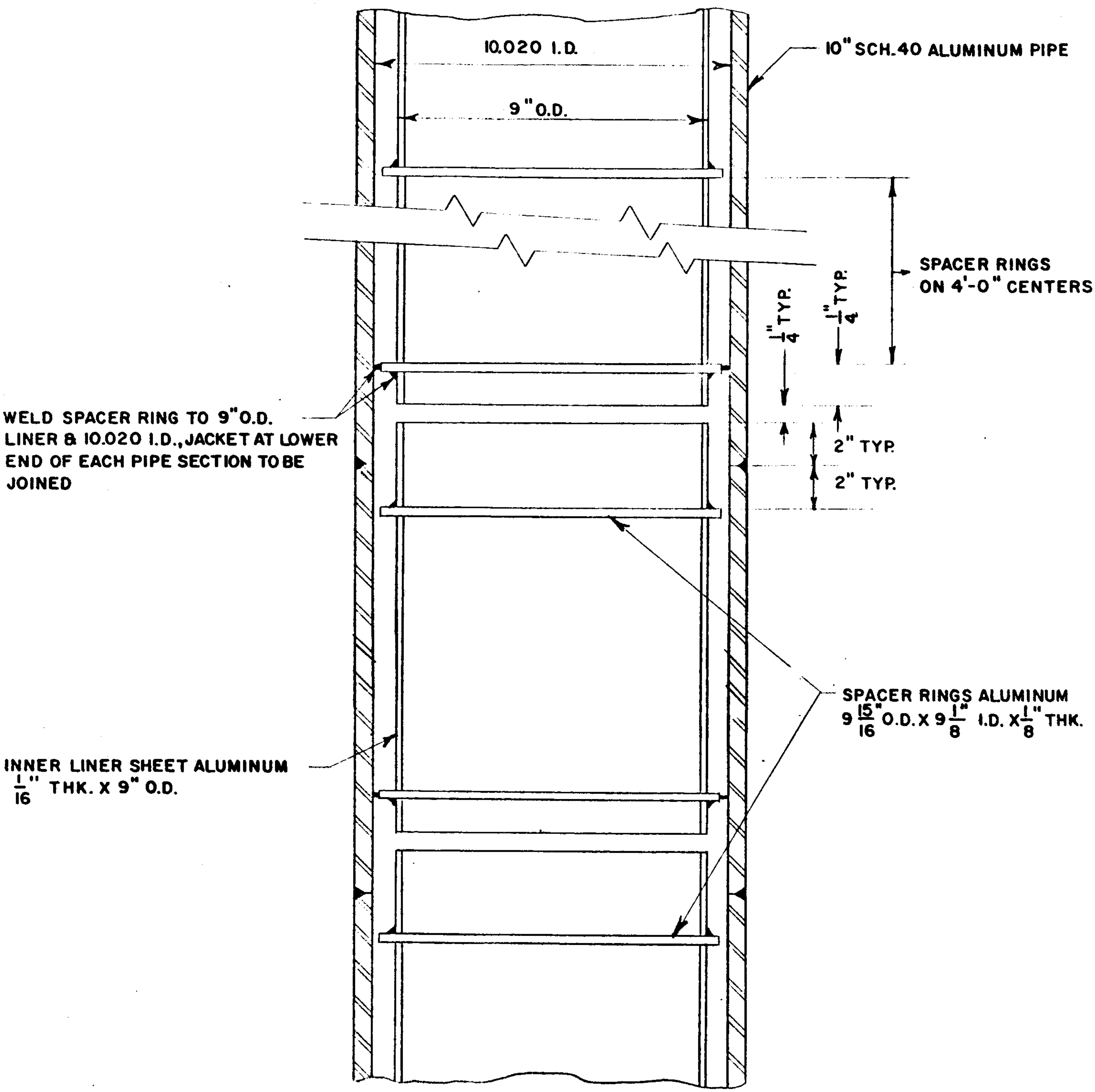


FIGURE 7

Typical Vent Line Detail (Section with Inner Liner)

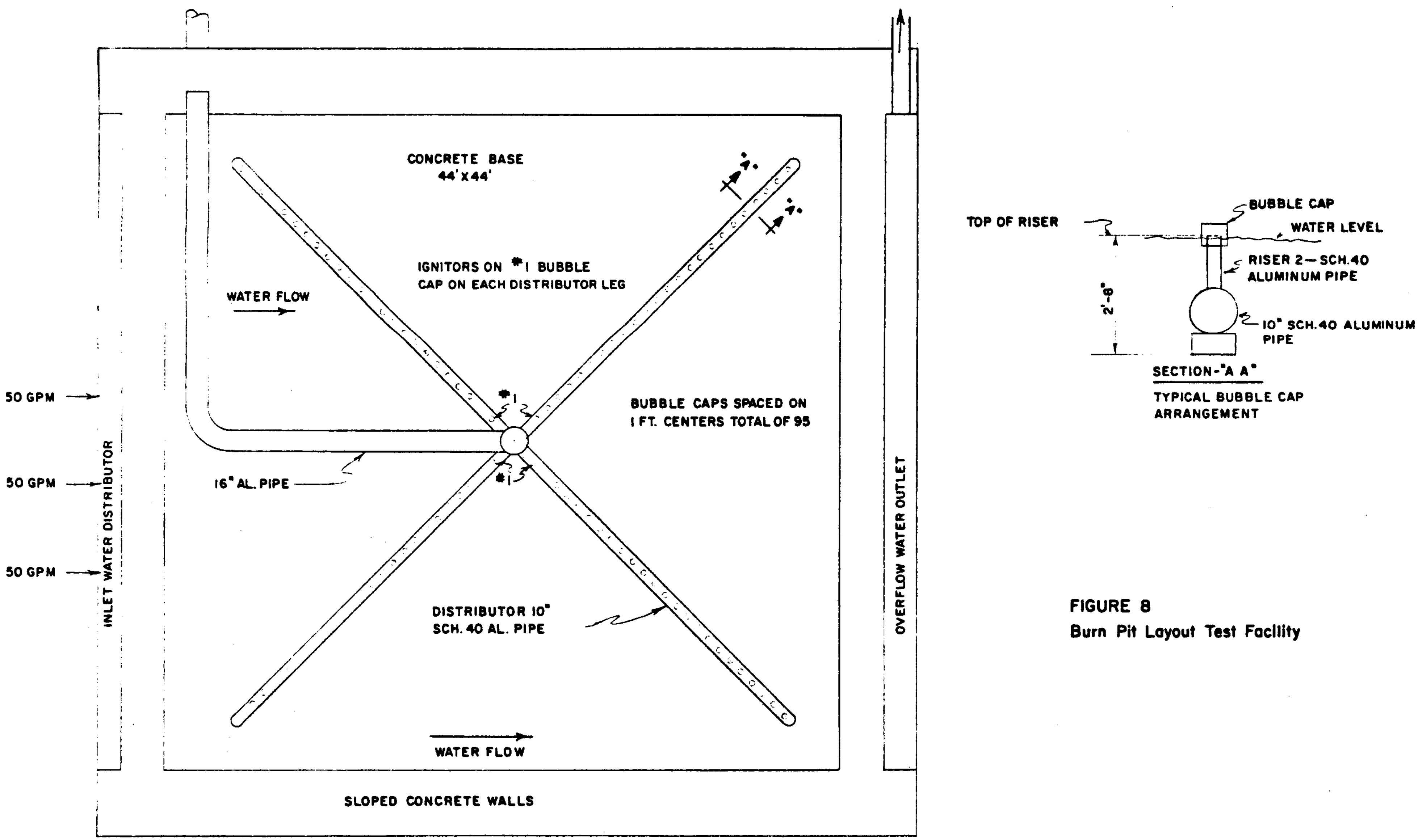


FIGURE 8
Burn Pit Layout Test Facility

(a) A four foot long section was equipped with a loosely fitting ring of polyurethane.

(b) The rest of the sections were installed with liner only.

In the two cases hydrogen gas was admitted to the space between liner and outside pipe.

Figure 8 indicates the layout of the burn pond. The piping system used in the pond will be used at complex 37 with a slight modification. This modification will consist of removal of the center distributor, and connect the four sections of pipe directly.

Figure 9 shows a cross section of the bubble cap used in the burn pond. The bubble cap is a standard cap, as used extensively in the chemical industry. Operation of the cap is as follows; at zero flow conditions water level is maintained somewhere between the top of the riser and top of the slots. As soon as pressure in the vent system develops, the water level between the riser and the cap is depressed until gas escapes through the slots and bubbles through the water to the surface of the pond.

The ignition system to be used for the burn pond at complex 37 was developed during the test program. Initial tests were made with a propane system, consisting of 4 small diameter tubes located in the four quadrants of the burn pond close to the center distributor. The mouth of the tubes protruded approximately one foot above the water level of the pond. Before hydrogen flow into the vent system was started, propane flow was started and the propane was ignited at the mouth of the tubes. The propane flow was maintained during the initial tests. The electrical system developed during the test program is shown in figure 10. The electrical lead to the Nichrome wire heater are brought up through the space between the riser and cap of the 4 bubble caps nearest to the center distributor.

The Nichrome heater element is mounted on the cap by means of two insulated pins through the cap. Two baffle plates protect the heater from splashing water and high wind velocities and at the same time enough open space is maintained between the plates to generate a combustible mixture at the heater wire as soon as hydrogen gas starts flowing.

The rate of hydrogen flow to the vent system was obtained by using a digital print-out of the electric weighting system of storage tank "D" at the test site. Temperature measurements were made at a number of points located along the vent line as indicated in figure 6. At the entrance to the vent system hydrogen pressure thermometer was used for temperature measurement. The pressure drop across the vent line was obtained with a bellow type pressure differential indicator.

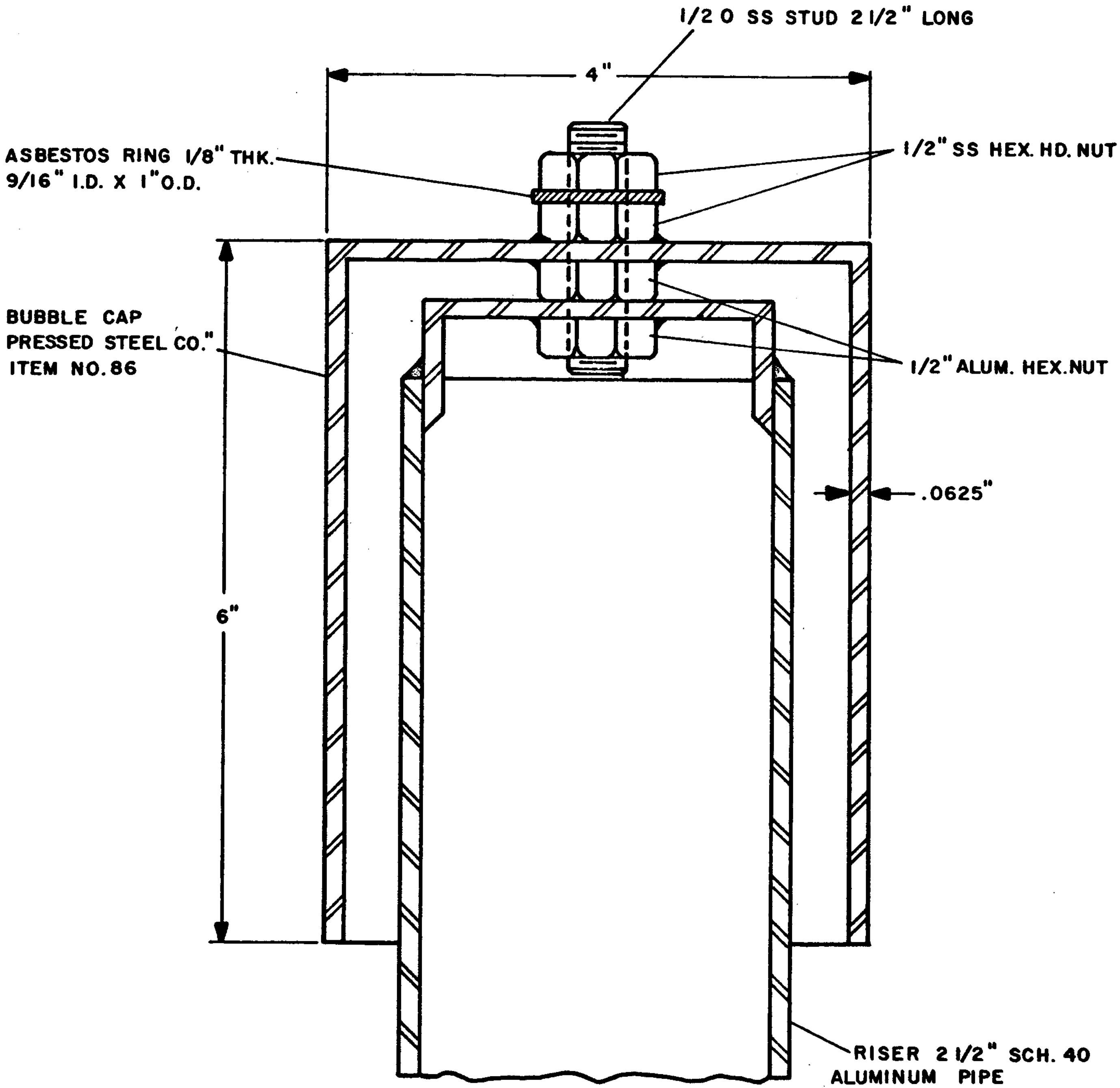


FIGURE-9

BUBBLE CAP LEVELING DESIGN

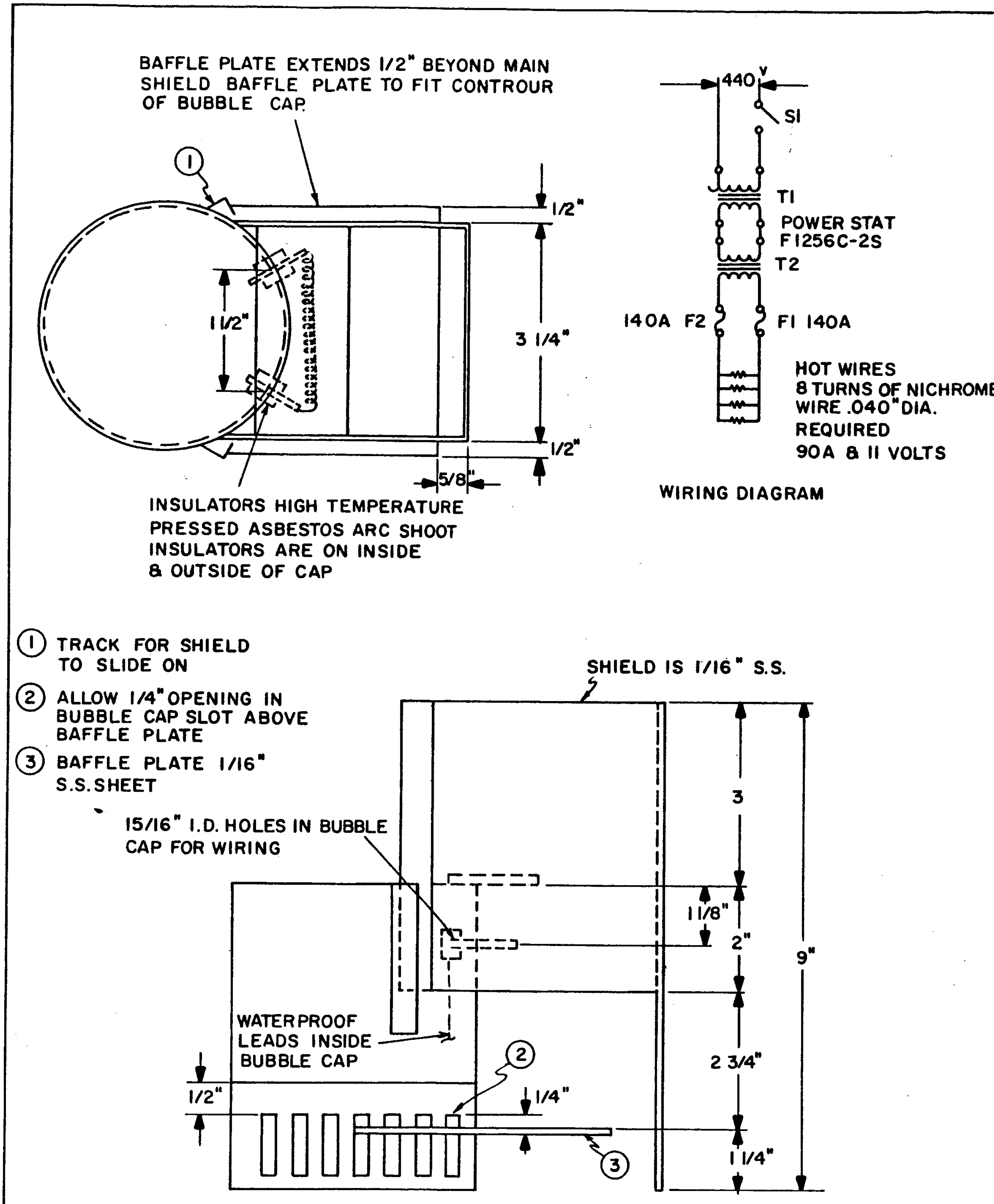


FIGURE 10

BURN PIT IGNITION SYSTEM

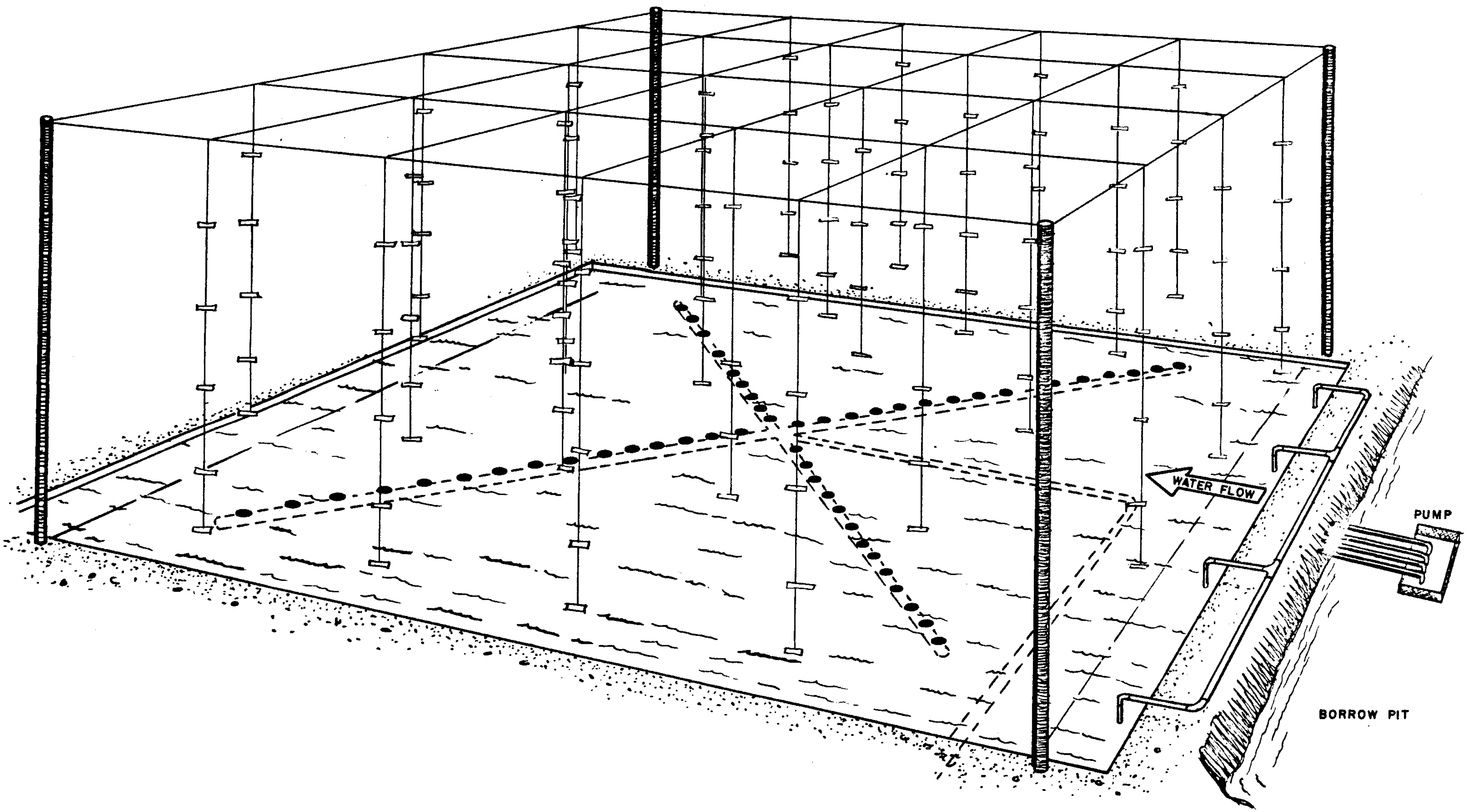


FIGURE 11
BURN PIT
TEMPERATURE PROFILE MEASURING SYSTEM

The distribution of heat around the burn pond was measure by a large number of temperature points. Figure 11 indicates the system used to obtain temperature above and around the burn pond. Four poles hold a wire suspension system from which streamers are supported. Each streamer is equipped with a number of stainless steel tabs. Temperature indicating paints were used on each of the tabs to give an indication of the temperature range, each tab was subjected to during the burning of hydrogen gas.

Discussion of Results

Tests were performed at hydrogen flowrates of 500 to 6000 pounds per hour. During all tests with flowrates in excess of 1000 lbs per hour the temperature at the inlet of the vent system was maintained at -420°F or less.

Insulation of Vent Line

The two types of insulation prevented the formation of liquid air on the outside of the line under all flow and prevalent weather conditions. The insulation actually is good enough to prevent the formation of fog in the air surrounding the line. A layer of frost is built up to a thickness of 1/2 to 3/4" during an 8 hour endurance test. The section insulated with polyurethane performed much better than the section containing the bare inner liner. For periods of 1-1/2 to 2 hours frost did not occur on the pipe. After this length of time, however, frost did cover the section. It appeared however, that this frost built up with time from the ends towards the center of the polyurethane insulated section and conduction along the heavy walled outer pipe probably contributed greatly. The layer of frost grew to about the same thickness as on the other sections of insulated line, once frost was formed.

It was quite clear that insulation of the type used is essential to keep the vent line, since liquid air formed on the expansion joints not equipped with insulation.

Pressure Drop Through Vent System

A pressure drop of 0.162 pounds per square inch at 7,000 SCFM was well under the maximum allowable pressure drop of 1 pound per square inch at this flowrate. At a maximum obtainable test flowrate of 19,300 SCFM of hydrogen, a pressure drop of 0.533 psi was incurred. Figure 11 shows the hydrogen flowrate versus pressure drop through the vent system.

Pressure drop through the vent system is a function of the vent line temperature. As the line cools down, the pressure drop for a specific

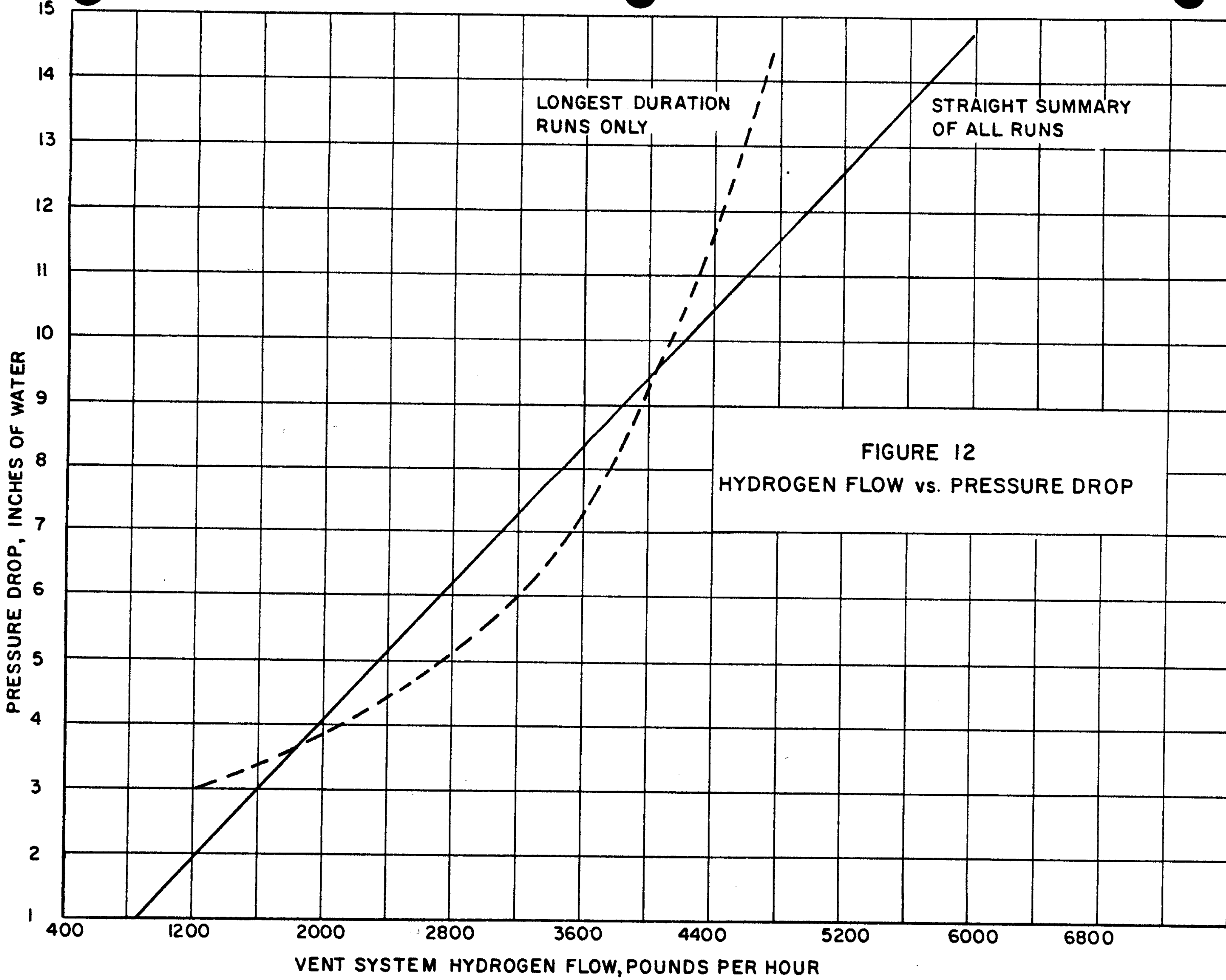


FIGURE 12
HYDROGEN FLOW vs. PRESSURE DROP

hydrogen flowrate decreases. Line cooldown is affected by the rate of flow, ambient temperature, and wind conditions. As can be seen in Appendix I, Data Summary, most tests were of short duration. Therefore, basing the pressure drop data on the longer runs, a parabolic curve as shown on Figure 11 is formed. This parabolic curve agrees with pressure drop flowrate theory.

Expansion Joint Performance

All expansion joints in the vent system were subjected to a total of 30-40 cycles. Expansion joints in and near the insulated vent line sections were subjected to the most severe service once temperature cycles were extreme. For instance, expansion joint No. 7 of figure 6 was found to lengthen .9 inches during a test with a flowrate of 3204 lbs of hydrogen per hour. The gas temperature at this point was approximately -390°F.

The complete assembly of the vent line was anchored at three points, as indicated in figure 6. With these anchors there was no visual movement or bending of the line.

Vent Line Temperatures

The temperature of the hydrogen in the vent line and the adjacent outside wall temperatures were recorded at points 150 feet apart throughout the entire length of the vent line. Figure 11 shows the line cooldown and hydrogen warmup during Test #5. Ambient temperature and wind direction and velocity are influencing factors on the hydrogen warmup in the vent line. In Test #5 equilibrium conditions were reached at T-70 minutes. The hydrogen flowrate was 3,204 pounds per hour. The average overall heat transfer coefficient of the unlined vent line was 1.5 BTU/(hour)(°F.)(ft.^{2}). The hydrogen temperatures in the lined vent pipe were too cold to obtain accurate temperatures for calculating a heat transfer coefficient.

Hydrogen and vent line temperatures at distances along the length of the vent line at specified flowrates are shown in Figure 13.

Burn Pond Water Temperatures

Water flowrates into the burn pond were maintained at 150 gpm throughout the tests. This flowrate was sufficient to keep the header feeding the distribution system free from ice and to maintain a fairly substantial flow of water out of the pond.

The splashing of water around the bubble caps caused a considerable rise in the temperature of the water in the pond. This is obvious, since droplets of water travel through the hydrogen flames. Part of the droplet vaporizes while the bulk returns to the pond as warm water. The vaporization of water is also demonstrated by the bright yellow-orange color of the flame. Samples of water taken from the pond and analyzed indicated a considerable salt content.

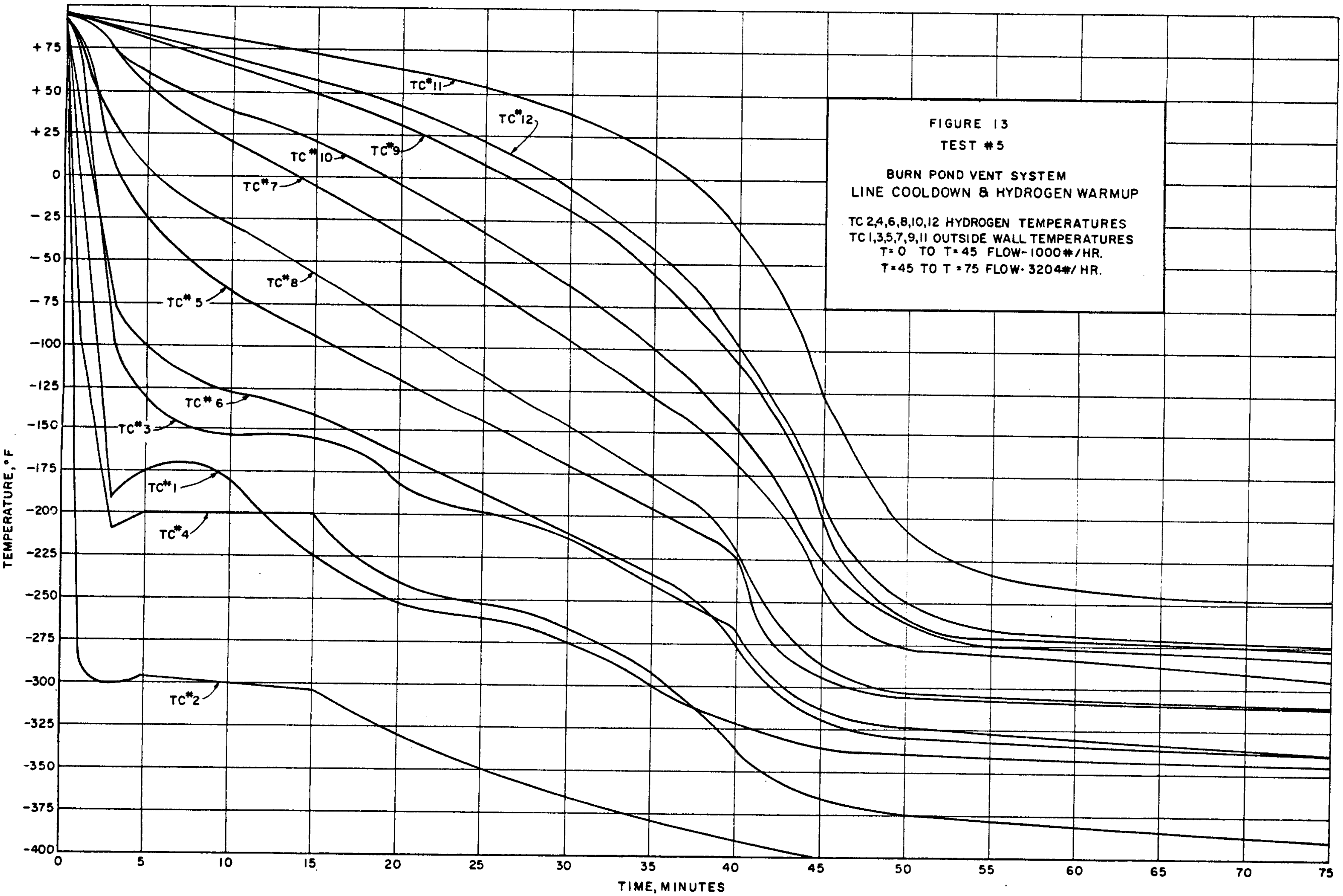


FIGURE 13
TEST #5
BURN POND VENT SYSTEM
LINE COOLDOWN & HYDROGEN WARMUP
TC 2,4,6,8,10,12 HYDROGEN TEMPERATURES
TC 1,3,5,7,9,11 OUTSIDE WALL TEMPERATURES
T=0 TO T=45 FLOW-1000#/HR.
T=45 TO T=75 FLOW-3204#/HR.
TC#11
TC#12
TC#9
TC#10
TC#7
TC#8
TC#5
TC#6
TC#3
TC#1
TC#4
TC#2
+75
+50
+25
0
-25
-50
-75
-100
-125
-150
-175
-200
-225
-250
-275
-300
-325
-350
-375
-400
TEMPERATURE, °F
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
TIME, MINUTES

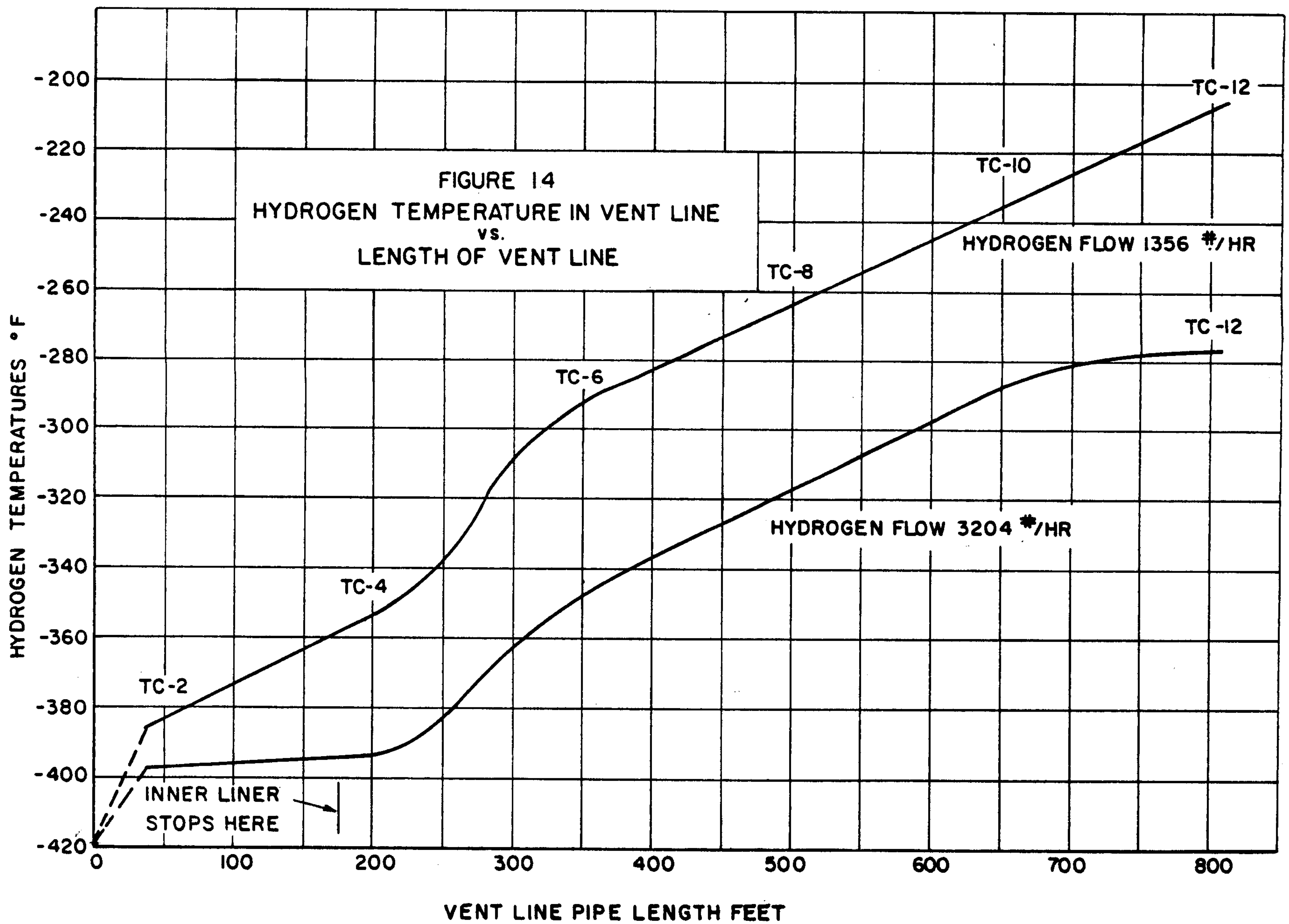


FIGURE 14
HYDROGEN TEMPERATURE IN VENT LINE
vs.
LENGTH OF VENT LINE

A maximum outlet water temperature of 140°F occurred during Test #5. The outlet water temperature was measured after the pond had been burning for fifty minutes at 1,000 pounds per hour and one hundred minutes at 3,204 pounds per hour. The water temperature rise was 66.6°F. Considerable surface boiling was observed during these tests. The water temperature rise during the 6,000 pounds per hour burn Test #6 was only 46.8°F. This lower water temperature rise is attributed to the fact that the 6,000 pounds per hour test only lasted thirty minutes and complete temperature equilibrium had not been reached.

Temperatures Around the Burn Pond

During the burn pond tests, flame and temperature patterns were obtained (Appendix I, Data Summary Tests #4 and #7). Test #7 was conducted under wind conditions of 15 to 22 miles per hour and at a higher hydrogen flow rate than Test #4 and gave the highest temperatures. The results indicate that the heat of the hydrogen flame is dissipated in the water and in the air of the immediate burn pit area. Radiation from the hydrogen flame is quite small. At sixteen feet above the burn pit maximum temperatures reached were less than 500°F at a hydrogen flowrate of 3,650 pounds per hour. Very high temperatures of 2,000°F exist only near the bubble caps. Temperatures ten feet downwind of the burn pit (40 feet from the center of the pit) were less than 300°F.

Ignition System

During the series of the tests an electrical ignition system was developed. An electrical system was chosen for easy serviceability. A number of problems had to be solved to make the electrical system reliable. For instance; the system has to operate with low and high wind velocities from all directions, during rainfall and with a fairly wide variety of flowrates of hydrogen gas. Basically ignition of a flammable mixture of hydrogen gas and air is simple; a high enough temperature (in excess of 1100°F) will ignite the hydrogen. A nichrome heater coil dissipating approximately 200 watts can be made to glow red (temperatures in excess of 1100°F) with the design indicated in figure 10. The protective covers prevent excessive cooling of the coil due to water splashing or high wind velocities. The proximity of the hot element and conducting wires to the bubble cap assumes adequate cooling to prevent over heating of the heater element. The conditions under which the nichrome coil electrical ignition system has been tested are as follows:

(1) Low flowrates of approximately 500 pounds per hour and high flowrates of 3,500 pounds per hour (Test #4). Repeatability of ignition at low flowrates was performed six times and at high flowrates eight times with reignition occurring each time.

(2) High winds 15 to 22 miles per hour and a low flow 654 pounds per hour.

(3) Under the same wind conditions and at 3,650 pounds per hour.

(4) Winds of 15 to 22 miles per hour and rain. Rain simulated with a fire nozzle (Items 2, 3 and 4 are Test #7, see Data Summary).

(5) The ignition system and burn pond were in continuous use burning hydrogen for seven hours and forty minutes simulating "hold conditions on countdown". Hydrogen was burned at varying flowrates (Test #5). At the end of the burning time the entire system was purged with nitrogen gas. Hydrogen was readmitted to the system and reignition occurred.

Bubble Caps

A total of 92 bubble caps is used in the distribution system of the burn pond. Pressure drop through the individual caps is mainly determined by the water level relative to the slots. This indicates, that quite accurate leveling of the caps is required to obtain uniform distribution of flow. Figure 9 indicates a screwed connection between riser and cap. Through this screwed connection adjustment of the cap is possible.

During the test program it was observed that visual inspection of the rate of bubbling of nitrogen gas through the caps was a satisfactory means to obtain good adjustment and even distribution of flow of hydrogen gas through all caps.

CONCLUSION

The tests carried out in this program indicate that the vent line, burn pond and ignition system tested will perform as required for the Saturn Vehicle Vent System.

The gas pocket formed in the annular space between the 9 inch liner and the 10 inch vent line exhibits excellent insulative qualities. Therefore, no liquid air will be formed on the vent line of the umbilical tower. The expansion bellows used in this run of pipe will also be lined.

The pressure drop through the vent system is well within the design conditions. The vent system can handle considerably higher flowrates than designed for with pressure drops within the safe range of the S-IV vehicle.

The expansion bellows performed as designed and showed no adverse effects from the large number of extreme temperature cycles experienced during the testing.

The burn pond water acts as a sink to collect a considerable fraction of the energy released by the burning hydrogen. A water flowrate of 150 GPM was sufficient to prevent water from freezing on the underwater hydrogen line even though the hydrogen entered the burn pond at -275°F. The air temperatures in the burn pond area were relatively cool and personnel and equipment can be present to within 50 feet. distance of the pond.

The burn pond and bubble cap distribution system handled flows up to 6,000 pounds per hour and without doubt could have handled much larger quantities.

The final bubble cap leveling design allows individual cap leveling and locking of each cap after leveling is complete.

The final design of the ignition system consisting of a hot nichrome wire coil performed very well under varying conditions of hydrogen flows, wind velocities, and rain and required a total of 60 kwh of power for 4 ignition systems.

APPENDIX I

DATA SUMMARY

VENT SYSTEM AND BURN POND

APPENDIX I

DATA SUMMARY

TEST #	1	2	3	3A	4
DATE	11/1/61	11/2/61	11/3/61	11/3/61	12/19/61
DEWAR PRESSURE PSIG	10	20	30	30	30
H_2 FLOW #/Hr.	1778	700	3114	1629	3220
H_2 TEMP. INTO VENT LINE °F	-422.5	-360	-423.2	-423.3	-420
H_2 TEMP. INTO BURN POND PIPE °F	-237	+50	-217	-167	--
PRESSURE DROP VENT LINE-INCHES OF WATER	2.5	--	9.0	2.25	--
WIND DIRECTION	NE	NE to E	E	NE	--
WIND VELOCITY MPH	10	10 to 12	15	15	--
BURN POND WATER FLOW GPM	150	150	150	150	150
TEMP. RISE °F	--	--	--	43.5	--
TYPE OF IGNITION SYSTEM	Acetylene Pilot	Acetylene Pilot	Acetylene Pilot	Acetylene Pilot	Nichrome Coil
IGNITION TIME SEC.	--	24	--	24	14
LENGTH OF TEST	67 Min.	35 Min.	50 Min.	35 Min.	40 Min.

APPENDIX I

DATA SUMMARY

TEST #	5	5	5	5	5
DATE	12/22/61	12/22/61	12/22/61	12/22/61	12/22/61
DEWAR PRESSURE PSIG	21	21	21	21	21
H_2 FLOW #/HR.	1000	3204	3068	1395	1356
H_2 TEMP. INTO VENT LINE °F	-420	-420	-420	-420	-420
H_2 TEMP. INTO BURN PIT PIPE °F	-188	-274	-271	-223	-205
PRESSURE DROP VENT LINE-INCHES OF WATER	--	6.76	6.25	3.06	2.72
WIND DIRECTION	SE-S	SE-S	SE-S	SE-S	SE-S
WIND VELOCITY MPH	4 to 10	4 to 10	4 to 10	4 to 10	4 to 10
BURN PIT WATER FLOW GPM	150	150	150	150	150
BURN PIT WATER TEMP. RISE °F	--	66.6	--	57.6	45
TYPE OF IGNITION SYSTEM	Nichrome Coil	Nichrome Coil	Nichrome Coil	Nichrome Coil	Nichrome Coil
IGNITION TIME SEC.	14	--	--	--	--
LENGTH OF TEST MIN.	50	100	75	60	175

APPENDIX I

DATA SUMMARY

TEST #	6	7	7	7
DATE	1/8/62	1/13/62	1/13/62	1/13/62
DEWAR PRESSURE PSIG	40	35	35	35
H_2 FLOW #/HR.	6000	654	1940	3650
H_2 TEMP. INTO VENT LINE °F	-420	-420	-420	-420
H_2 TEMP. INTO BURN PIT PIPE °F	-281	+57	-100	-275
PRESSURE DROP VENT LINE-INCHES OF WATER	14.82	1	4	8.1
WIND DIRECTION	N	N-NE	N-NE	N-NE
WIND VELOCITY MPH	0 to 5	15 to 22	15 to 22	15 to 22
BURN PIT WATER FLOW GPM	150	150	150	150
BURN PIT WATER TEMP. RISE °F	46.8	--	--	46
TYPE OF IGNITION SYSTEM	Nichrome Coil	Nichrome Coil	Nichrome Coil	Nichrome Coil
IGNITION TIME SEC.	--	14	--	14
LENGTH OF TEST MIN.	30	15	15	15

DATA SUMMARY

BURN PIT TEMPERATURE PROFILE

Heat sensitive paints were employed in obtaining the air temperatures in the burn pit area. A network of wires were strung over the burn pit. Sheets of 1" x 3" x 1/16" stainless steel were painted with the heat sensitive paints and then hung at various elevations over the burn pit. Each individual paint was sensitive to one specific temperature as follows:

Paint - Heat Sensitive to Temperature	
1	113
2	200
3	300
4	400
5	500
6	750
7	1000
8	1250
9	1500
10	2000

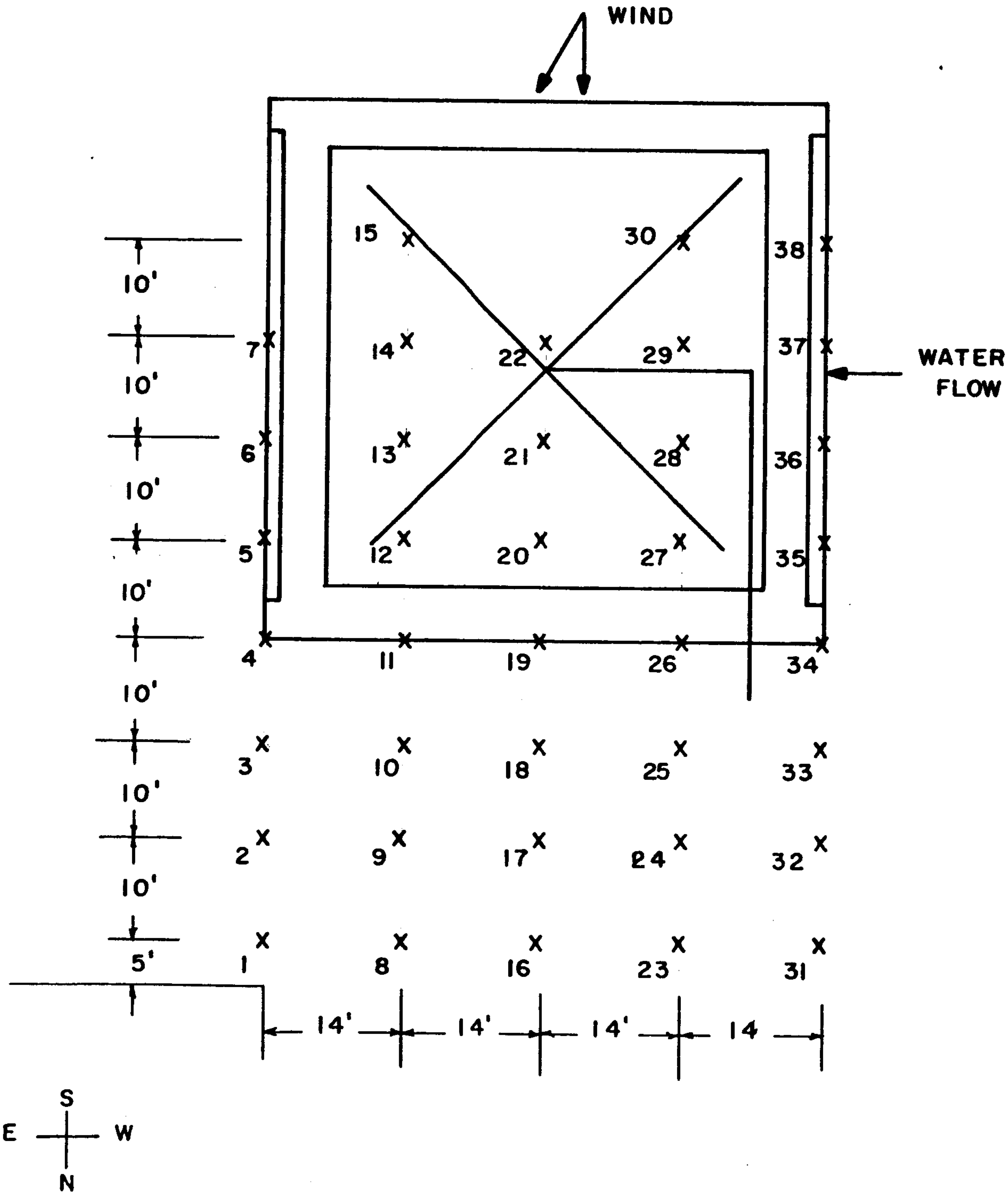
It can be seen that should the 300°F paint melt and not the 400°F paint at one specific temperature point, the temperature at this point is somewhere between 300 and 400°F. The temperature would be recorded as between 300 and 400°F.

DATA SUMMARY

BURN PIT TEMPERATURE PROFILE

TEST # 4

TEMPERATURE POINT & LOCATION



DATA SUMMARY

BURN PIT TEMPERATURE PROFILE

TEST #4

HEIGHT ABOVE PIT / TEMP. POINT	1'	6'	11'	16'	21'
1	Below 113	Below 113	Below 113	Below 113	Below 113
2	Below 113	Below 113	Below 113	Below 113	Below 113
3	Below 113	Below 113	113 to 200	Below 113	Below 113
4	113 to 200	113 to 200	200 to 300	113 to 200	Below 113
5	113 to 200	200 to 300	300 to 400	113 to 200	Below 113
6	400 to 500	300 to 400	300 to 400	200 to 300	113 to 200
7	400 to 500	--	500 to 750	300 to 400	113 to 200
8	Below 113				
9	Below 113				
10	200 to 300	113 to 200	113 to 200	113 to 200	--
11	200 to 300	300 to 400	300 to 400	113 to 200	--
12	2000	1500 to 2000	1500 to 2000	400 to 500	--
13	500	1500 to 2000	1500 to 2000	400 to 500	--
14	2000	1250 to 1500	1000 to 1250	400 to 500	--
15	2000	400 to 500	500 to 750	400 to 500	--
16	Below 113				
17	Below 113	113 to 200	113 to 200	Below 113	--
18	113 to 200	113 to 200	200 to 300	113 to 200	--
19	200 to 300	300 to 400	300 to 400	113 to 200	--
20	1500 to 2000	500 to 750	200 to 300	113 to 200	--

NOTE - Temperature in °F

DATA SUMMARY

BURN PIT TEMPERATURE PROFILE

TEST #4

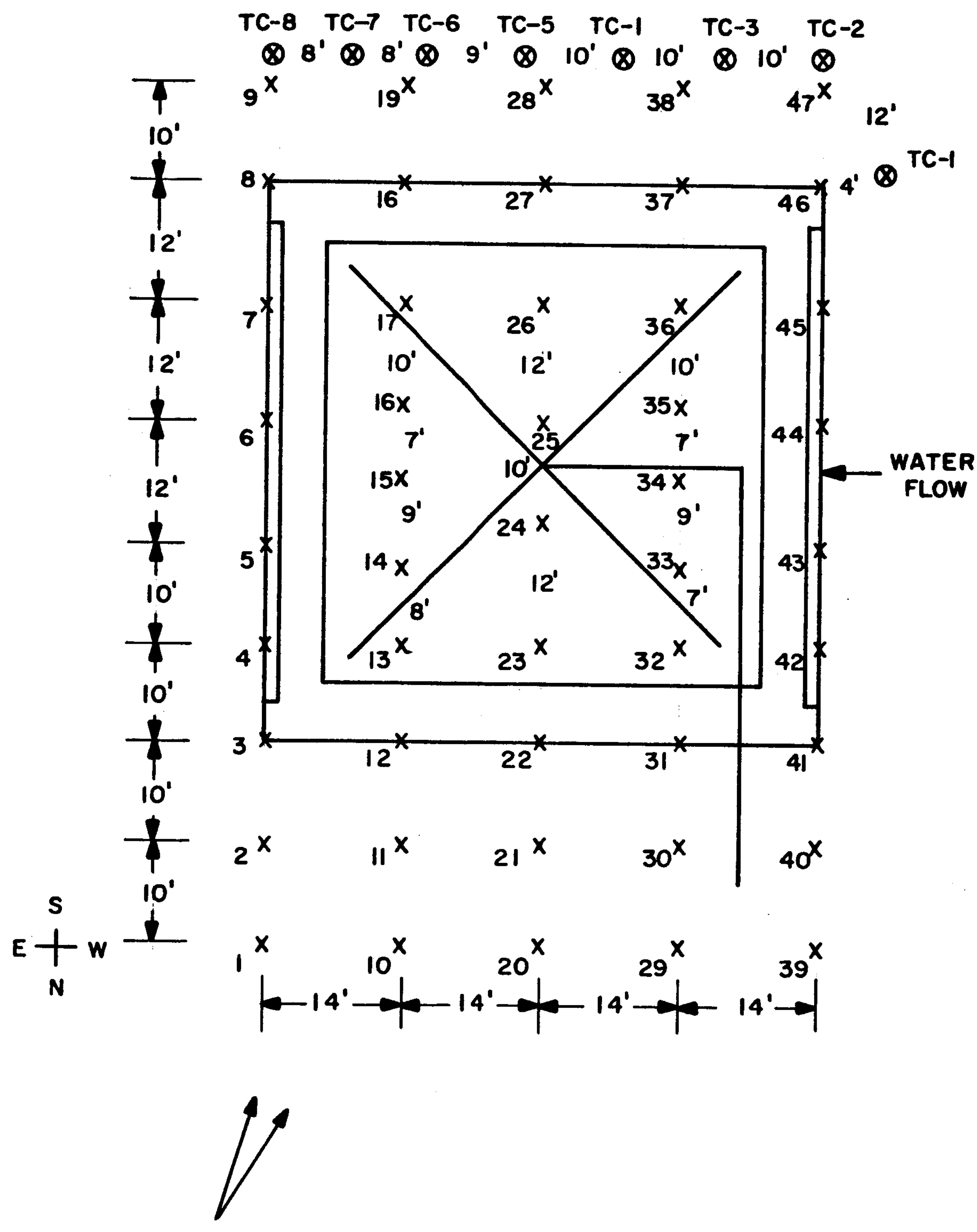
HEIGHT ABOVE PIT TEMP. POINT	1'	6'	11'	16'	21'
21	2000	500 to 750	400 to 500	300 to 400	--
22	1500 to 2000		400 to 500	400 to 500	--
23	113 to 200	113 to 200	113 to 200	Below 113	Below 113
24	113 to 200	200 to 300	113 to 200	113 to 200	113 to 200
25	200 to 300	113 to 200	200 to 300	200 to 300	--
26	300 to 400	113 to 200	200 to 300	113 to 200	--
27	--	750 to 1000	200 to 300	200 to 300	--
28	200 to 300	200 to 300	200 to 300	200 to 300	--
29	750 to 1000	500 to 750	400 to 500	200 to 300	--
30	2000 Higher	1500 to 2000	1500 to 2000	300 to 400	--
31	Below 113				
32	Below 113				
33	113 to 200	113 to 200	113 to 200	113 to 200	Below 113
34	3' 113 to 200	8' 113 to 200	13' Below 113	18' Below 113	
35	3' 200 to 300	8' 200 to 300	13' 113 to 200	18' 113 to 200	
36	3' 113 to 200	8' 113 to 200	13' Below 113	18' Below 113	
37	3' 113 to 200	8' 113 to 200	13' 113 to 200	18' Below 113	
38	2' 113 to 200	7' 200 to 300	12' 113 to 200	17' 113 to 200	

NOTE - Temperature in °F

DATA SUMMARY

BURN PIT TEMPERATURE PROFILE
TEST # 7

TEMPERATURE POINT & LOCATION



DATA SUMMARY

BURN PIT TEMPERATURE PROFILE

TEST #7

HEIGHT ABOVE PIT	1'	6'	11'	16'	21'
TEMP. POINT					
1	Below 113 →				
2	Below 113 →				
3	Below 113 →				
4	Below 113 →				
5	Below 113 →				
6	Below 113 →				
7	Below 113 →				
8	Below 113 →				
9	Below 113 →				
10	Below 113 →				
11	Below 113 →				
12	Below 113 →				
		3'	6'	11'	16'
13	2000+	500 to 750	Below 113	Below 113	Below 113
14	1500 to 2000	1500 to 2000	1250 to 1500	Below 113	Below 113
15	400 to 500	300 to 400	200 to 300	Below 113	Below 113
16	200 to 300	200 to 300	200 to 300	Below 113	Below 113
17	2000+	1500 to 2000	200 to 300	Below 113	Below 113
18	--	1500 to 2000	200 to 300	113 to 200	Below 113
19	--	113 to 200	113 to 200	113 to 200	Below 113
20	--	--	--	--	--
	1'	6'	11'	16'	
21	Below 113	Below 113	Below 113	Below 113	--
22	113 to 200	113 to 200	Below 113	Below 113	

NOTE - Temperature in °F

<u>DATA SUMMARY</u>

<u>BURN PIT TEMPERATURE PROFILE</u>

<u>TEST #7</u>

HEIGHT ABOVE PIT	1'	6'	11'	16'	21'
TEMP. POINT					
23	200 to 300	200 to 300	200 to 300	113 to 200	--
24	1500 to 2000	500 to 750	300 to 400	200 to 300	--
25	1500 to 2000	750 to 1000	300 to 400	113 to 200	--
	1'	2'	6'	11'	16'
26	750 to 1000	400 to 500	300 to 400	113 to 200	Below 113
	1'	6'	11'	16'	
27	300 to 400	300 to 400	200 to 300	113 to 200	--
28	200 to 300	200 to 300	200 to 300	113 to 200	
29	--	--	--	--	--
30	Below 113				
31	Below 113				
	1'	3'	6'	11'	16'
32	400 to 500	200 to 300	113 to 200	Below 113	Below 113
33	2000 +	1500 to 2000	300 to 400	113 to 200	Below 113
34	1250 to 1500	1250 to 1500	300 to 400	200 to 300	Below 113
35	1500 to 2000	1500 to 2000	1200 to 1500	300 to 400	200 to 300
36	2000 +	1500 to 2000	1500 to 2000	1250 to 1500	400 to 500
	1'	6'	11'	16'	21'
37	300 to 400	500 to 750	500 to 750	300 to 400	--
38	200 to 300	200 to 300	200 to 300	200 to 300	--
39	Below 113				
40	Below 113				
41	Below 113				
42	113 to 200	113 to 200	113 to 200	Below 113	Below 113

NOTE - Temperatures in °F.

DATA SUMMARY

BURN PIT TEMPERATURE PROFILE

TEST #7

HEIGHT ABOVE PIT / TEMP. POINT	1'	6'	11'	16'	21'
43	500 to 750	300 to 400	113 to 200	113 to 200	Below 113
44	200 to 300	300 to 400	113 to 200	113 to 200	Below 113
45	200 to 300	400 to 500	300 to 400	200 to 300	113 to 200
46	200 to 300	300 to 400	400 to 500	400 to 500	300 to 400
47	113 to 200	200 to 300	200 to 300	300 to 400	300 to 400

TEST #7
THERMOCOUPLE READINGS

1	+195
2	+175
3	215
4	285
5	225
6	---
7	86
8	86

NOTE - Temperatures in °F.

APPENDIX 2

ILLUSTRATION SUMMARY

VENT LINE AND BURN PIT

APPENDIX 2

ILLUSTRATION SUMMARY

VENT LINE & BURN PIT

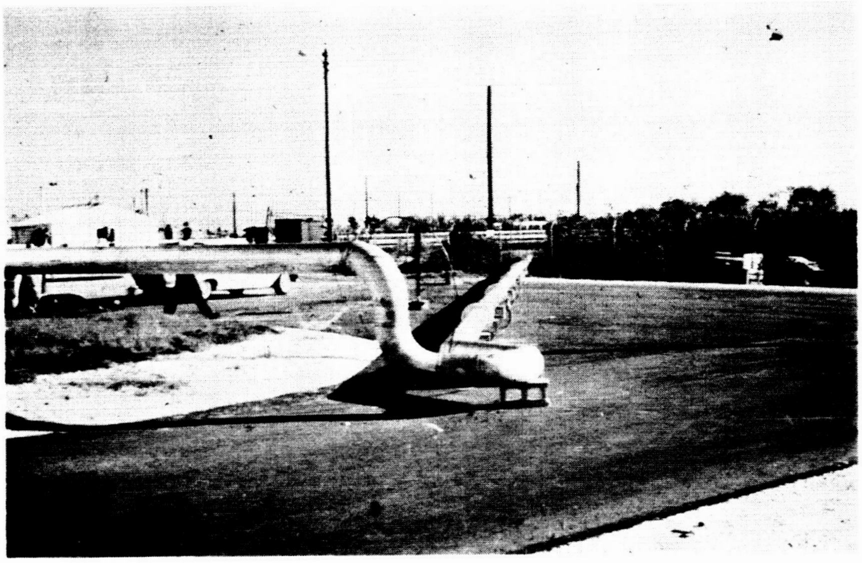


ILLUSTRATION 1
PRETEST VENT LINE CONTAINING INNER LINER

ILLUSTRATION 2

FIRST ANCHOR POINT IN VENT LINE

APPENDIX 2

ILLUSTRATION SUMMARY

VENT LINE & BURN PIT

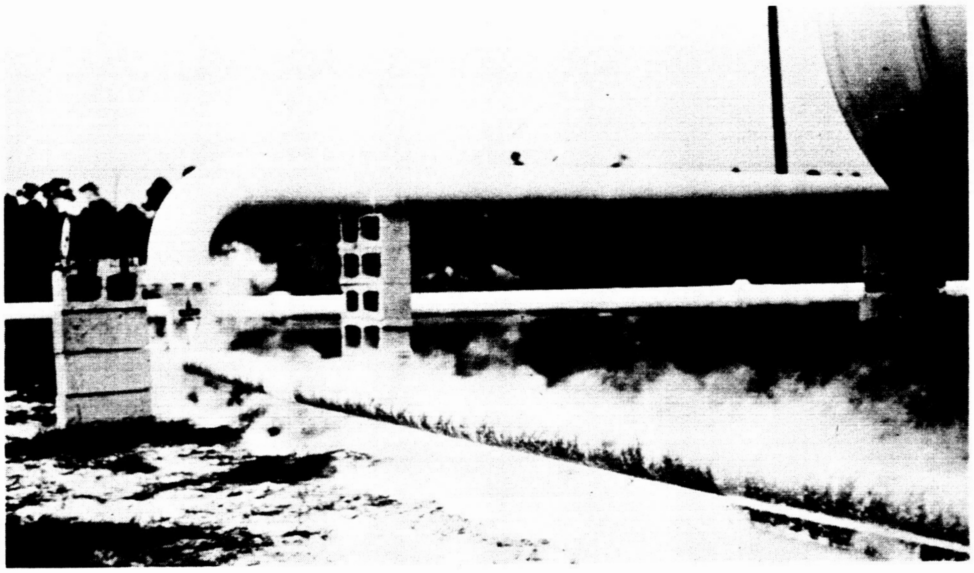


ILLUSTRATION 3
HYDROGEN ENTERING THE VENT SYSTEM
NOTE LIQUID AIR ON LINE LEADING TO VENT SYSTEM

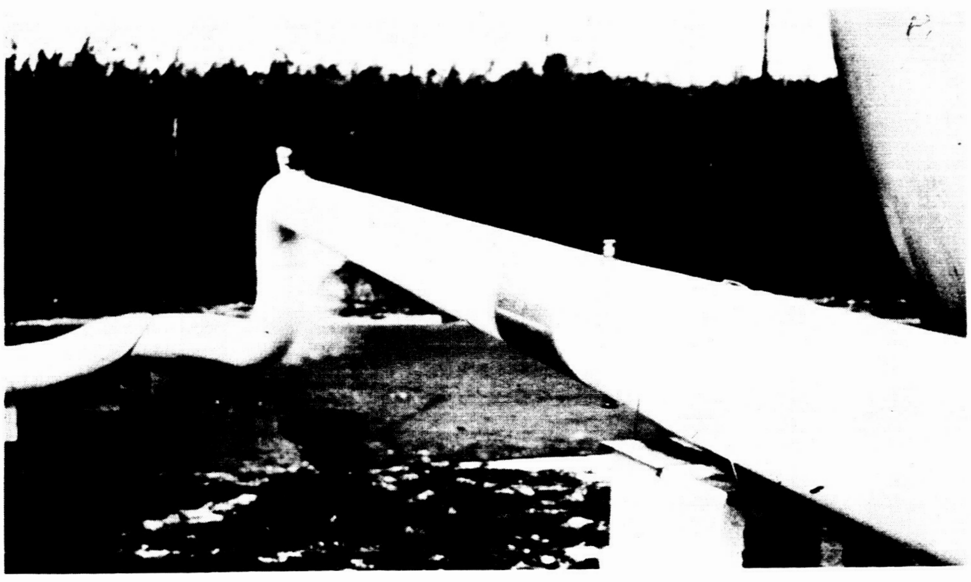


ILLUSTRATION 4
POLYURETHANE FROST FREE SECTION OF 10 INCH VENT LINE.
LIQUID TEMPERATURES RECORDED AT INLET TO VENT SYSTEM
25 FEET UPSTREAM OF THE POLYURETHANE.

APPENDIX 2

ILLUSTRATION SUMMARY

VENT LINE & BURN PIT

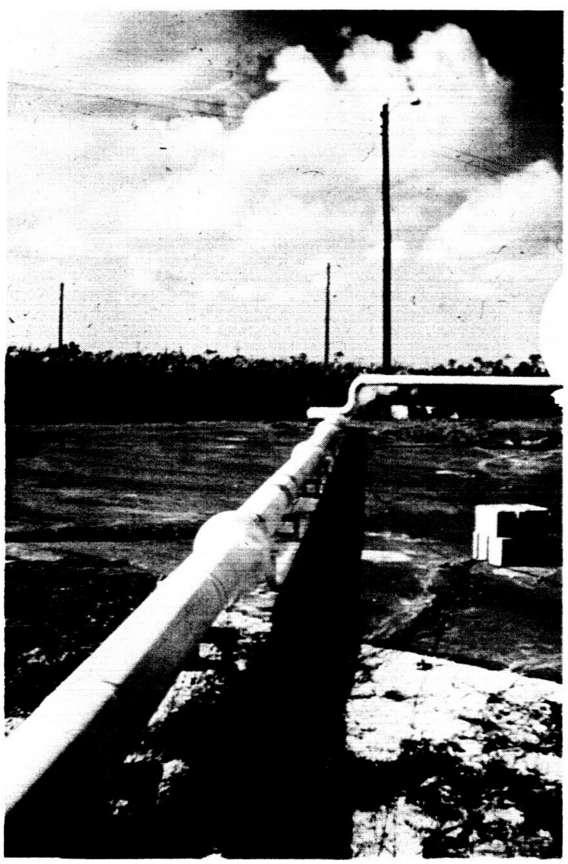


ILLUSTRATION 5
VENT LINE WITH INNER LINER.
NOTE ONLY INDICATION OF LIQUID AIR FORMATION IS ON EXPANSION JOINTS AND ONE UNLINED ELBOW IN BACKGROUND.

ILLUSTRATION 6
VENT LINE WITHOUT THE INNER LINER.
LIQUID AIR FORMATION CAN BE NOTED.

APPENDIX 2

ILLUSTRATION SUMMARY

VENT LINE & BURN PIT

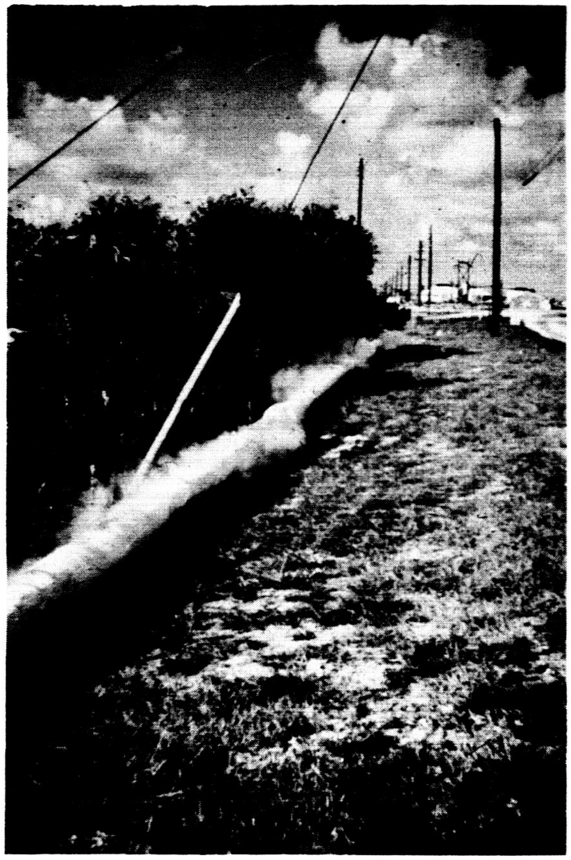


ILLUSTRATION 7
FROST FORMATION ON VENT LINE

ILLUSTRATION 8
BUBBLE CAP WATER LEVEL

APPENDIX 2

ILLUSTRATION SUMMARY

VENT LINE & BURN PIT

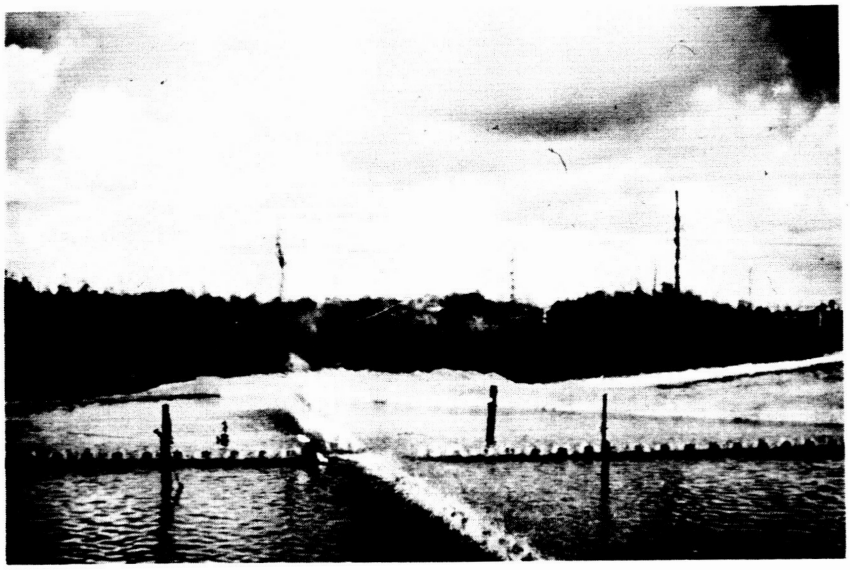


ILLUSTRATION 9
H_2 BURNING - ACETYLENE IGNITION SYSTEM.
NOTE VIOLENT BUBBLING AROUND BUBBLE CAPS.
(NORMAL AT HIGH FLOWRATES)

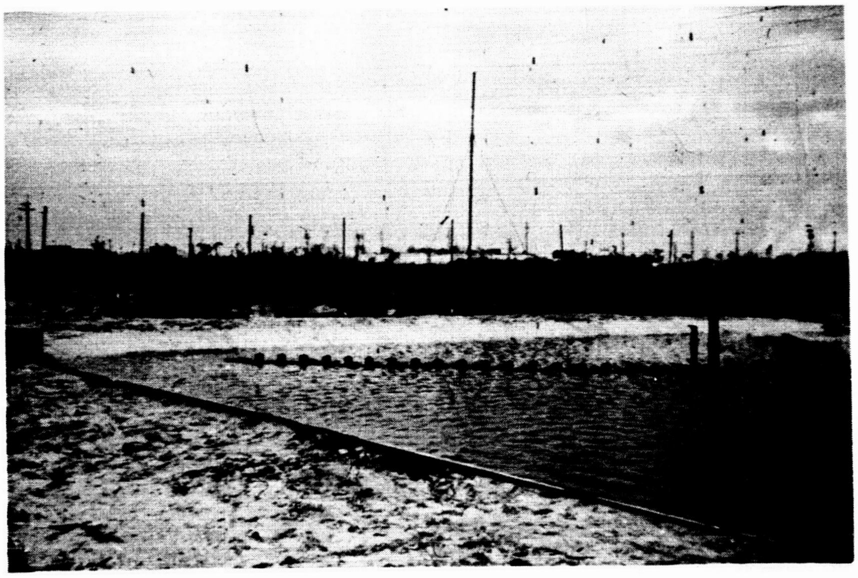


ILLUSTRATION 10
H_2 BURNING WITH NICHROME COIL IGNITION SYSTEM.
NOTE TEMPERATURE PROFILE MEASURING STRINGERS.

APPENDIX 2

ILLUSTRATION SUMMARY

VENT LINE & BURN PIT

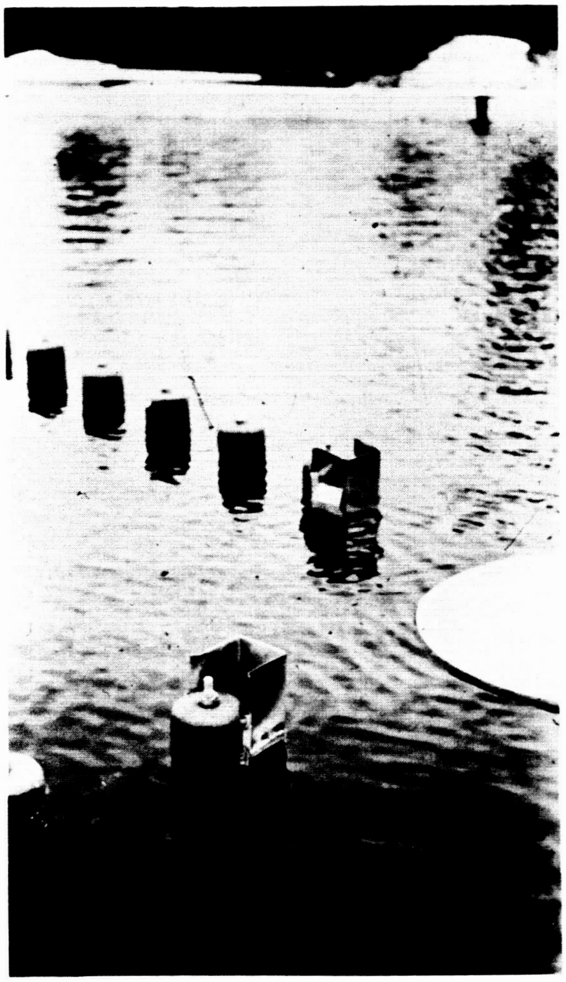


ILLUSTRATION 11
IGNITERS ON 2 LEGS
OF THE H_2 DISTRIBUTOR

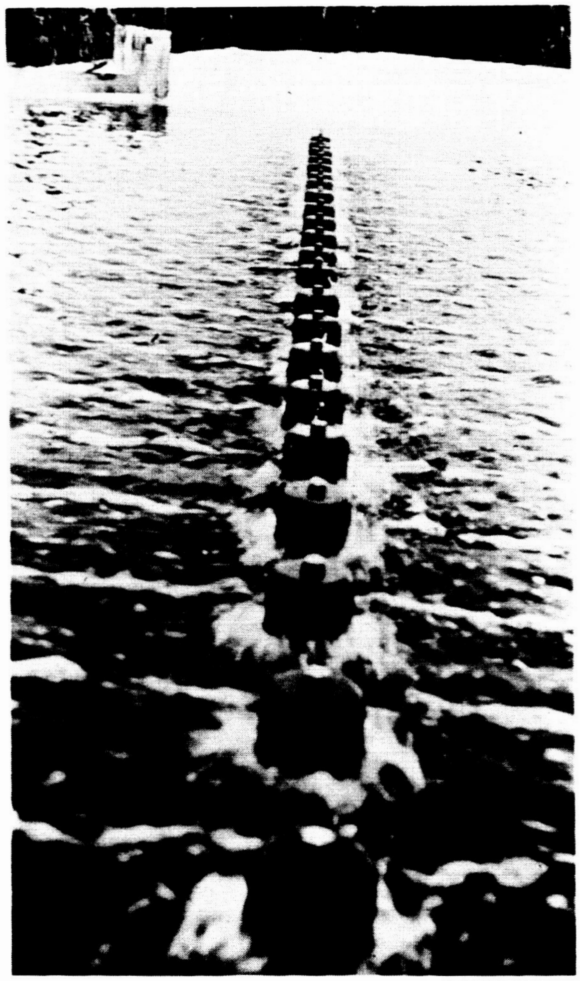


ILLUSTRATION 12
NOTE FOAMY WATER APPEARANCE AFTER TEST.
CONSIDERABLE SURFACE BOILING
OCCURRED DURING TEST.

APPENDIX 2

ILLUSTRATION SUMMARY

VENT LINE & BURN PIT

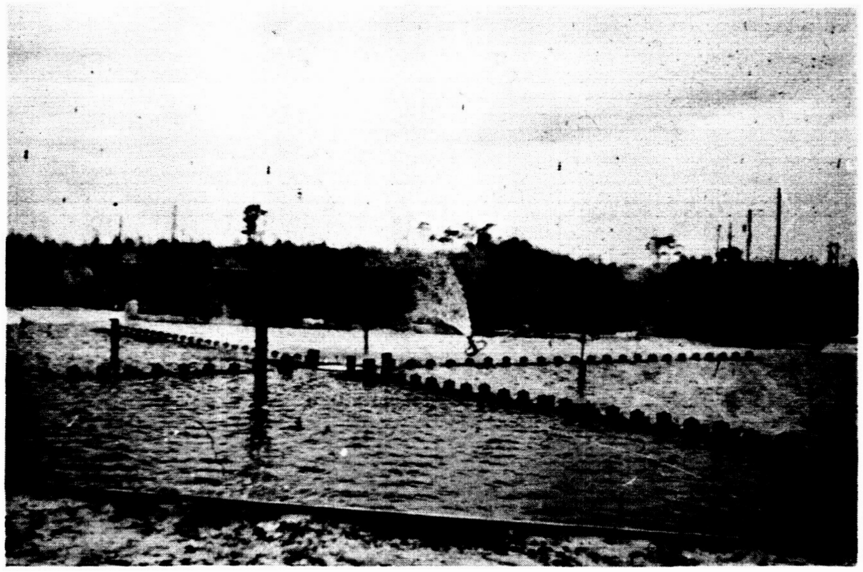


ILLUSTRATION 13
IGNITION OF H_2 UNDER SIMULATED RAIN CONDITIONS

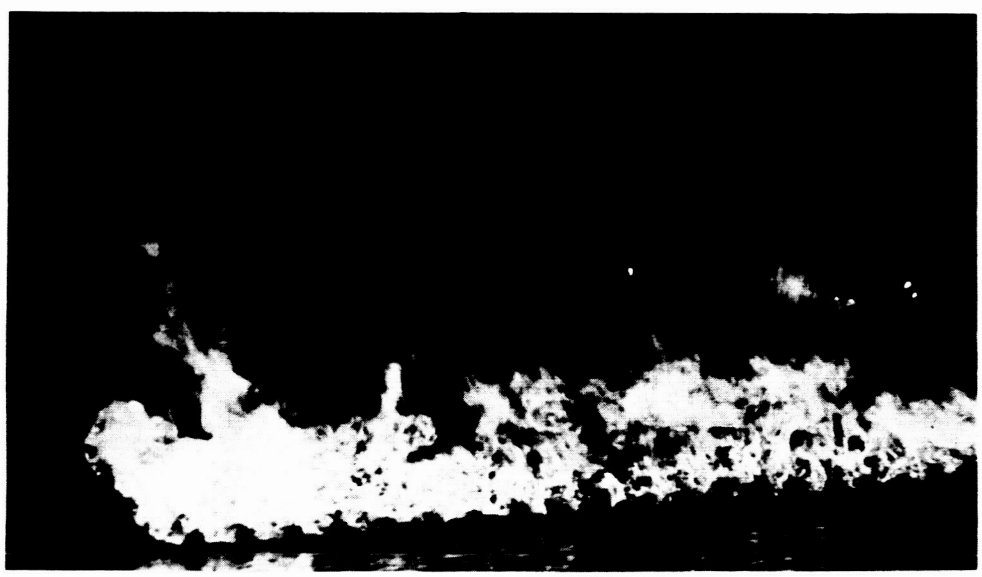


ILLUSTRATION 14
HYDROGEN BURNING AT NIGHT.
COLOR DUE TO SALTS IN BURN PIT WATER

V Liquid Hydrogen Subcooler

Introduction

This report covers the experiments performed on the subcooler in conjunction with the cold gas vacuum pump which will be part of the hydrogen loading system for the Saturn Space Vehicle on Complex 37.

The purpose of these experiments was to obtain data and information to:

(1) Verify the subcooler design for tubeside pressure drop. A maximum flow of 2000 GPM of hydrogen must flow through the subcooler with a limited pressure drop.

(2) Verify subcooler design to perform required subcooling. Overall heat transfer coefficients will be determined to confirm this.

(3) Determine the effect of liquid level on subcooling.

(4) Confirm design of liquid level indicating and control system.

(5) Confirm design of pressure control system.

(6) Determine optimum cooldown and operational procedures.

At the fast fill flowrate of 2000 GPM, subcooling is not required. However, during the replenish period when flowrates are less than one-fourth of this rate, subcooling is essential to maintain liquid quality at the vehicle. Tests were carried out at flowrates from 13 to 640 GPM.

Subcooler Design

The subcooler is designed to remove a maximum of 50000 BTU/Hr. of heat at a liquid hydrogen flowrate of 500 gpm. Figure 14 shows a cross section of the subcooler. Liquid enters through the six inch diameter line and is distributed over a number of copper tubes of one inch diameter. The liquid is collected again and flows through the mandrel of the tube bundle to the outlet. The baffle shown just before the outlet provides the possibility to return almost all liquid present in the cross country line, after lift off of the vehicle. Cooling of the liquid flowing through the tubes is provided by liquid vaporizing from the space around the tube. The pressure over this boiling liquid is artificially maintained at a pressure of 7-9 psia in order to lower the temperature of the boiling liquid.

Insulation is provided by a perlite filled space maintained at a vacuum of 50 microns of Hg or less.

Test Apparatus

The test equipment used to obtain the information presented in this report consists of the subcooler, controls, cold gas vacuum pump, and vacuum jacketed piping between the subcooler and cold gas pump which will be used on the Saturn loading system.

Figure 15 illustrates the flow diagram used for the test.

Valve PCV-42, a fully automatic vacuum jacketed valve designed for vacuum pressures at liquid hydrogen temperatures, maintains a pressure below atmospheric above the boiling liquid hydrogen.

Valve LCV-9 controls the subcooler shellside liquid level. LCV-9 receives its signal from either a differential pressure indicator level sensor and indicator or a condensation type level sensor and indicator. This valve is also fully automatic. Temperatures of the liquid hydrogen into and out of the subcooler were measured with a hydrogen vapor pressure bulb type temperature indicator.

Flowrates of the liquid hydrogen through the subcooler were obtained with the digital print-out of an electronic weighting system using load cells on a 28,000 gallon supply vessel. Pressure drop across the subcooler was measured with a bellows type differential pressure indicator.

Hydrogen flowrates through the cold gas pump were measured with a calibrated orifice meter run. Temperatures of the hydrogen entering and leaving the pump were measured with hydrogen vapor pressure thermometers and calibrated thermocouples.

Discussion of Results

The subcooler was tested at flowrates ranging from 13 to 640 GPM. The 640 GPM was the maximum obtainable flowrate at the test site. The subcooler was tested both independent of the pump and with the pump running at speeds of 400 and 500 RPM.

Subcooler Pressure Drop

The subcooler pressure drop was obtained in two ways. During the initial tests the pressure drop was determined across pressure taps located in the 3" x 5" vacuum jacketed transfer line of the test site. This pressure drop is not the true pressure drop across the subcooler since both at inlet and outlet a change of diameter from 3 to 6 inches adds part of the velocity head changes to the pressure drop across the subcooler. During later tests, pressure drop was measured between taps located directly in the six inch inlet and outlet line of the subcooler.

Pressure drop at a flowrate of 500 gpm was 4.9 inches of water, when flowing in the proper direction through the subcooler. For reverse flow, which will be practiced when a drain sequence of the vehicle

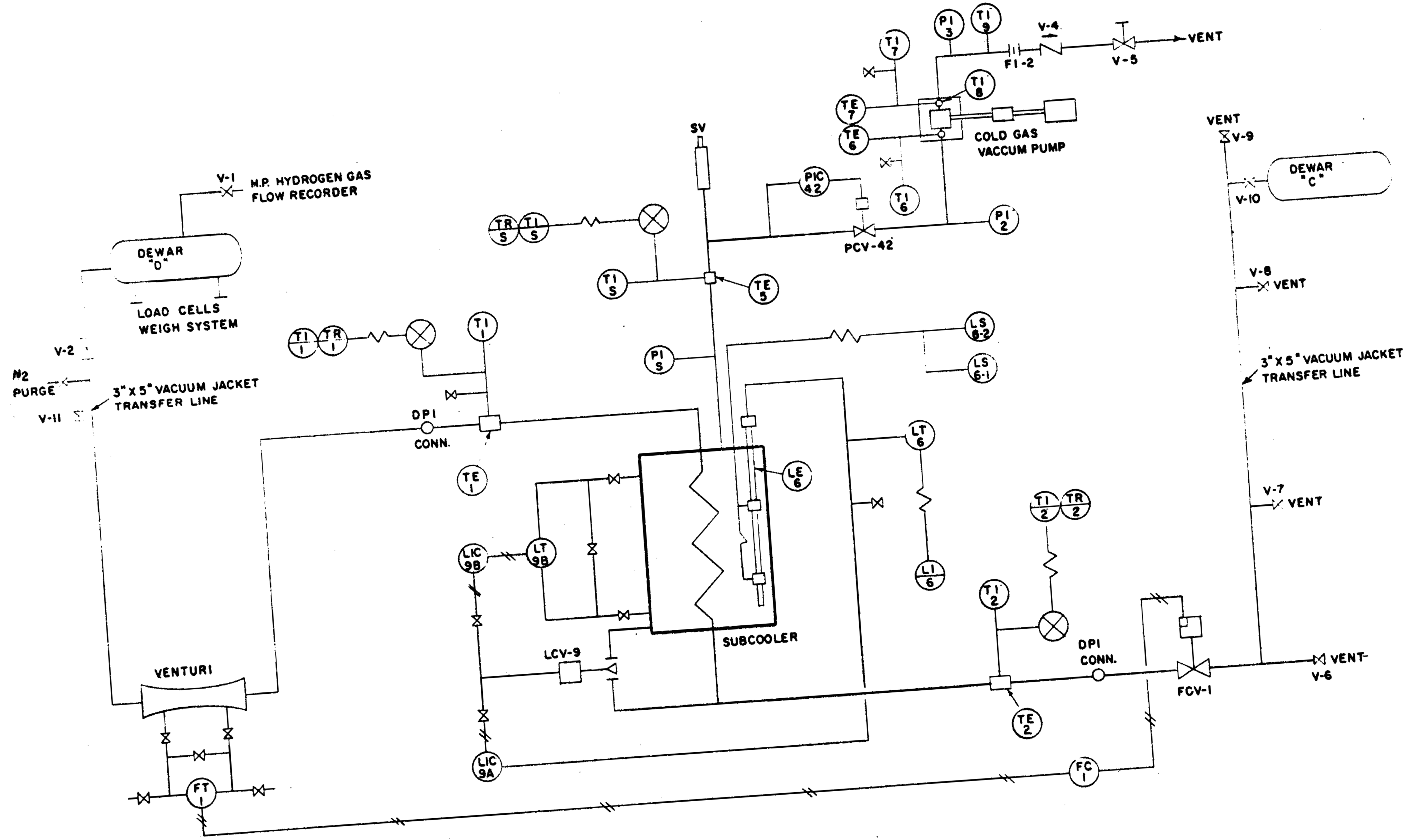


FIGURE 15
Subcooler & Cold Gas Vacuum Pump Test Flow Diagram

is in process, the pressure drop was found to be slightly less. For instance, with a flow rate of 458 gpm in reverse direction, the pressure drop was measured to be 2.95 inches of water as compared to 4.25 inches of water at the same flowrate in the normal direction. This difference is explained however, by the difference in elevation of inlet and outlet nozzles. The corrected pressure drop for flow in the normal direction is 3.9 inches of water (.14 psi) at 500 gpm. The calculated pressure drop at a flowrate of 2000 gpm is of the order of 2.25 psi.

Subcooling

The amount of cooling achieved by the subcooler is a function of:

(a) Liquid level maintained.

(b) Pressure maintained over the boiling liquid on the shell side.

(c) Hydrogen flowrate through the tubes.

Figure 16 shows the amount of heat transferred as a function of liquid level. In order to obtain this data, pressure over the boiling liquid on the shellside was maintained at a constant value of 8.54 psia and the inlet temperature and flowrate of the liquid entering the subcooler was maintained at -421.45^{o}F and 71.2 gpm respectively. The data indicates that the heat transfer coefficient is independent of level over a wide area, since total amount of heat transferred is proportional to the liquid level and consequently the surface area of the tubes wetted by the boiling liquid. At the low flowrate the overall heat transfer is very much limited by the coefficient inside the tube. At high flowrates of the order of 500 gpm heat transfer coefficients of the order of 130 BTU/Hr.Ft^{2} ^{o}F were observed. At the high flowrates 6,000 to 7,000 BTU/Hr can be transferred from the liquid flowing through the tubes to the liquid boiling on the shell side.

Under actual operating conditions it is expected that two distinct flowrates will be maintained during the replenishing period. The high flowrate will be of the order of 500 gpm and the low flowrate of the order of 20 gpm. An examination of the data shows that a temperature change of approximately 1.25^{o}F at a flowrate of 500 gpm and 3^{o}F at a flowrate of 20 gpm can be expected. Heat gain into the liquid in the transfer line will be approximately 1,000 BTU/Hr and the average flowrate will be equal to the vehicle loss rate of 60 gpm. At this rate the temperature rise of the liquid in the line will be approximately 2^{o}F. It is apparent, that the liquid will enter the vehicle with two different temperatures, one of which will be .75^{o}F above and the other 2.25^{o}F below the temperature of the liquid entering the subcooler.

Liquid Level Control System

The condensation probe type liquid level indicator LI-6 and the level

HEAT TRANSFER VS LIQUID LEVEL
TYPICAL HYDROGEN FLOW
71.26 PM@ 25 PSIA T-1 CONSTANT
@ 421.45°F DATA FROM RUN #7
11-10-61

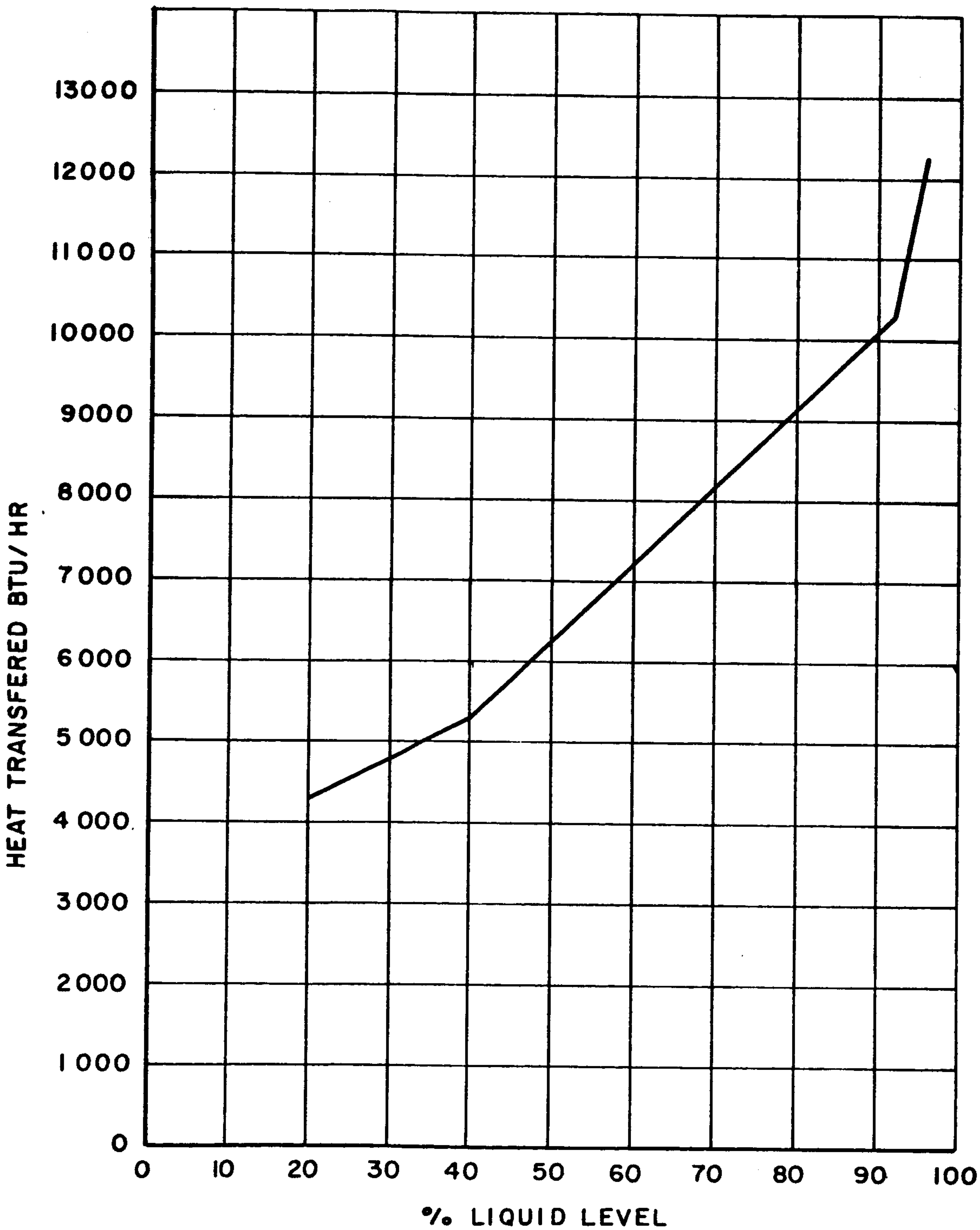


FIGURE 16

control system LIC-9A and LCV-9 functioned very well. LIC-9A and LCV-9 held the liquid level constant regardless of how rapidly the tubeside flow was changed. The low liquid level light (LSG-1) and the high liquid level indicating light (LSG-2) performed as designed.

The differential pressure level indicating system did not function well. It was apparent that a differential pressure level indicating system is unsuitable for hydrogen service where the entire range of liquid level is 2 inches of water. This system will be eliminated from the level control system.

Pressure Control System

Pressure control valve PCV-42 performed well in maintaining a constant pressure over the boiling liquid hydrogen.

Conclusions

In order to achieve the desired results in the operation of the subcooler for the hydrogen loading system, the following conditions are to be met:

(1) Maintain a high liquid level of 90% on the shell side of the subcooler.

(2) Operate the cold gas vacuum pump at a speed of 512 rpm.

(3) Set pressure controller PIC-42 at a low value of 5 psia. PCV-42 will then open wide at high replenishing flowrates and the cold gas vacuum pump will be the controller. At low replenishing flowrates the temperature of the liquid bath will be reduced and consequently a low temperature of the liquid in the tubes will be obtained.

APPENDIX 1

DATA SUMMARY

SUBCOOLER

APPENDIX I

DATA SUMMARY

Test Run	1	2	2	2	2
Date	1/3/62	1/4/62	1/4/62	1/4/62	1/4/62
Time at Equilibrium	11:40 A.M.	12:32	12:46	12:25	12:56
H_2 Flow - lbs./min.	74.3	155.2	155.2	155.2	155.2
GPM	124.3	261	261	261	261
PI-1 - PSIA	14.75	14.75	14.75	14.75	14.75
TI-1 - ^oF	421.30	421.25	421.32	421.25	421.13
TI-4 - ^oF	422.80	422.48	421.78	422.80	421.54
TI-5 - ^oF	423.48	423.48	423.48	423.48	423.48
ΔP - Inches H_2O	1.32	2.72	2.72	2.72	2.72
ΔT_m	1.29	1.54	1.92	1.308	2.15
$\dot{Q}$ - BTU/Hr.	16,360	26,340	9,630	33,180	8,790
U	45.8	65.8	19.3	97.8	15.72
Liquid Level, %	50 to 55%	50 to 55	30 to 33	66%	25%
Pump Suction - PSIA	-	-	-	-	-
Pump Flow - lbs./min.	1.34	2.3	-	-	-
Remarks	No Pump, Slow Cooldown	No Pump	Data of importance gained on Run #2 is pressure drop across subcooler liquid levels held low to find best level.		

DATA SUMMARY - (Continued)

Test Run	2	2	2	2	3
Date	1/4/62	1/4/62	1/4/62	1/4/62	1/5/62
Time at Equilibrium	1:00	1:21	1:52	2:01	-
H_2 Flow - lbs./min.	98.5	80.56	188.4	244.1	62.1
GPM	165.2	135.2	316	410	104.2
PI-1 - PSIA	-	-	-	-	-
TI-1 - ^oF	-	-	-	-	-
TI-4 - ^oF	-	-	-	-	-
TI-5 - ^oF	-	-	-	-	-
ΔP - Inches, H_2O	1.56	1.35	3.8	5.64	1.21
ΔT_m	-	-	-	-	-
Q - BTU/Hr.	-	-	-	-	-
U	-	-	-	-	-
Liquid Level, %	-	-	-	-	-
Pump Suction - PSIA	-	-	-	-	-
Pump Flow - lbs./min.	-	-	-	-	-

Remarks: Experimented on LIC-9 and PCV-42 and Level Probes.

DATA SUMMARY - (Continued)

Test Run	3	3	4	4	4
Date	1/5/62	1/5/62	1/8/62	1/8/62	1/8/62
Time at Equilibrium	2:16	-	10:24	10:44	10:45
H_2 Flow - lbs./min.	127.8	3.20	102.3	315	315
GPM	214	538	172	530	530
PI-1 - PSIA	7.88	-	11.74	11.74	11.74
TI-1 - ^oF	120.35	-	421.77	421.75	421.5
TI-4 - ^oF	421.60	-	422.77	422.80	422.7
TI-5 - ^oF	427.1	-	424.15	424.85	424.03
ΔP - Inches, H_2O	1.96	9.62	1.6	9.3	9.3
ΔT_m	6.1	-	2.54	2.53	2.69
Q - BTU/Hr.	22,000	-	14,080	45,600	52,200
U	13.85	-	21.3	69.5	74.6
Liquid Level, %	30 to 40%	-	47%	60%	60%
Pump Suction - PSIA	-	-	-	-	-
Pump Flow - lbs./min.	1.835	-	1.192	3.86	4.36
Remarks	Experimented on LIC-9 and PCV-42 and Level Probes.				

DATA SUMMARY - (Continued)

Test Run	5	6	6	7	7
Date	1/8/62	1/9/62	1/9/62	1/10/62	1/10/62
Time at Equilibrium	4:00	1:36	1:53	10:06	10:09
H_2 Flow - lbs./min.	76.8	103.4	103.4	42.3	42.3
GPM	124.3	174.0	174.0	71.2	71.2
PI-1 - PSIA	11.0	11.74	11.25	8.54	8.54
TI-1 - ^{o}F	419.75	420.57	420.37	421.43	421.45
TI-4 - ^{o}F	424.52	424.05	424.00	423.53	423.20
TI-5 - ^{o}F	425.25	424.84	425.1	426.68	426.68
ΔP - Inches, H_2O	1.33	1.69	1.69	1.11	1.11
ΔT_m	2.37	2.06	2.462	4.12	4.29
Q - BUT/Hr.	49,840	49,650	51,800	12,270	10,220
U	81.0	92.6	81.0	11.45	9.18
Liquid Level, %	85%	78.4%	75%	96%	92%
Pump Suction - PSIA	9.82	10.76	10.27	6.07	6.07
Pump Flow - lbs./min.	4.21	4.2	4.38	1.038	.865
Remarks	Higher Liquid Levels for Better Efficiency.				

DATA SUMMARY - (Continued)

Test Run	7	7	7	7	7
Date	1/10/62	1/10/62	1/10/62	1/10/62	1/10/62
Time at Equilibrium	10:11	10:13	10:14	10:16	10:18
H_2 Flow - lbs./min.	42.3	42.3	42.3	42.3	42.3
GPM	71.2	71.2	71.2	71.2	71.2
PI-1 - PSIA	8.54	8.54	8.54	8.54	8.54
TI-1 - ^oF	421.45	421.45	421.45	421.45	421.45
TI-4 - ^oF	423.13	423.05	422.94	422.88	422.80
TI-5 - ^oF	426.68	426.68	426.68	426.68	426.68
ΔP - Inches, H_2O	1.11	1.11	1.11	1.11	1.11
ΔT_m	4.33	4.39	4.44	4.51	4.52
Q - BUT/Hr.	9,800	9,340	8,715	3,360	7,880
U	8.71	8.18	7.55	7.14	6.72
Liquid Level, %	88	82	75%	72%	68%
Pump Suction - PSIA	6.07	6.07	5.83	5.83	5.83
Pump Flow - lbs./min.	.83	.79	.7375	.707	.667
Remarks	Run #7 Made to Show Subcooling VS Liquid Level LIC-9V Shot when Subcooler was flooded.				

DATA SUMMARY - (Continued)

Test Run	7	7	7	7	7
Date	1/10/62	1/10/62	1/10/62	1/10/62	1/10/62
Time at Equilibrium	10:23	10:31	10:36	10:45	10:20 A.M.
H_2 Flow - lbs./min.	42.3	42.3	42.3	42.3	42.3
GPM	71.2	71.2	71.2	71.2	71.2
PI-1 - PSIA	8.54	8.54	8.54	8.54	8.54
TI-1 - ^oF	421.45	421.45	421.45	421.45	421.45
TI-4 - ^oF	422.47	422.25	422.19	421.82	422.60
TI-5 - ^oF	426.68	426.68	426.68	426.68	426.68
ΔP - Inches, H_2O	1.11	1.11	1.11	1.11	1.11
ΔT_m	4.66	4.76	4.84	5.02	4.63
Q - BTU/Hr.	5,835	4,660	4,320	2,152	6,720
U	4.82	3.79	3.42	1.65	5.58
Liquid Level, %	52%	32%	20%	0	56%
Pump Suction - PSIA	5.83	5.83	5.83	3.88 to 5.83	5.83
Pump Flow - lbs./min.	.483	.395	.365	.182	.569
Remarks	Kept LIC-9V Closed and Recorded Temperature In and Out VS Time and Liquid Level. (See Figure 3)				

DATA SUMMARY - (Continued)

Test Run	7	7	7	7	8
Date	1/10/62	1/10/62	1/10/62	1/10/62	1/10/62
Time at Equilibrium	10:26	10:38	10:34	1:52	5:42
H_2 Flow - lbs./min.	42.3	42.3	42.3	60.5	305
GPM	71.2	71.2	71.2	101.6	512
PI-1 - PSIA	8.54	8.54	8.54	9.28	10.76
TI-1 - ^{o}F	421.45	421.45	421.45	420.69	422.74
TI-4 - ^{o}F	422.40	422.0	422.14	425.75	424.00
TI-5 - ^{o}F	426.68	426.68	426.68	426.22	425.37
ΔP - Inches, H_2O	1.11	1.11	1.11	1.2	9.14
ΔT_m	4.75	5.09	4.85	2.052	1.93
Q - BTU/Hr.	5,530	3,800	4,010	42,240	52,900
U	4.48	2.87	3.19	79.1	105.3
Liquid Level, %	44%	12%	28%	86.0	75 to 80
Pump Suction - PSIA	5.83	5.83	5.83	8.29	10.00
Pump Flow - lbs./min.	.468	.321	.34	3.56	4.48

DATA SUMMARY - (Continued)

Test Run	8	9	9	10	11
Date	1/10/62	1/11/61	1/11/61	1/11/61	1/11/62
Time at Equilibrium	6:18	11:28	11:40	1:35	4:45
H_2 Flow - lbs./min.	305	62	327	111.8	43.3
GPM	512	104	548	187.5	64.3
PI-1 - PSIA	11.74	10.76	12.63	9.27	7.3
TI-1 - ^oF	422.34	422.28	422.40	423.48	422.70
TI-4 - ^oF	423.45	424.22	423.76	425.96	426.70
TI-5 - ^oF	424.84	425.38	424.40	426.23	427.5
ΔP - Inches, H_2O	9.14	1.21	9.67	1.89	-
ΔT_m	1.87	1.97	1.195	1.07	2.682
Q - BTU/Hr.	48,000	15,880	60,000	35,200	22,850
U	98.7	31	193	126.5	32.75
Liquid Level, %	75 to 80	70%	100%	95%	80.9%
Pump Suction - PSIA	10.76	6.87	12.24	7.8	6.81
Pump Flow - lbs./min.	4.06	1.375	5.18	2.94	1.887

DATA SUMMARY - (Continued)

Test Run	11	11	11	11	12
Date	1/11/62	1/11/62	1/11/62	1/11/62	1/12/61
Time at Equilibrium	5:15	5:25	5:41	5:55	3:14
H_2 Flow - lbs./min.	70.2	107.6	183	310	18
GPM	117.9	180.5	307	520	30.2
PI-1 - PSIA	8.3	9.28	10.02	11.01	5.82
TI-1 - ^{o}F	422.8	422.9	422.9	422.8	423.86
TI-4 - ^{o}F	426.15	425.3	424.62	424.14	427.97
TI-5 - ^{o}F	426.80	426.22	425.8	425.18	428.55
ΔP - Inches, H_2O	1.25	1.83	3.52	8.56	-
ΔT_m	1.845	1.87	1.914	1.616	1.97
Q - BTU/Hr.	30,960	34,080	43,400	57,300	9,760
U	64.5	70.2	88.2	136.3	19.1
Liquid Level, %	77.8%	73%	77%	85%	80.9%
Pump Suction - PSIA	7.8	8.89	9.53	10.52	5.15
Pump Flow - lbs./min.	2.582	2.841	3.67	4.85	0.86

DATA SUMMARY - Continued

Test Run	12	12	12	12	12
Date	1/12/61	1/11/62	1/11/62	1/11/61	1/11/61
Time at Equilibrium	3:44	8:30	9:30	10:30	11:15
H_2 Flow -- lbs/min	45.3	27.9	18.51	15.61	13.62
GPM	76	46.8	31.1	26.21	22.88
P_1 -- PSIA	17.8	17.4	14.8	12.5	12.0
P_2 -- PSIA	8.6	7.0	6.7	6.6	6.5
P_s -- PSIA	7.2	6.33	6.07	5.83	5.83
T_1 -- ^oF	422.87	422.50	423.45	424.47	424.72
T_2 -- ^oF	426.62	427.68	427.90	427.98	428.05
T_s -- ^oF	427.55	428.17	428.37	428.53	428.53
ΔP -- Inches H_2O	1.15	-	-	-	-
ΔT_m	2.32	2.12	1.895	1.71	1.61
Q -- BTU/HR	22,560	-	-	-	-
U	37.5	34.7	22.0	16.2	14.32
Liquid Level %	80.9	82.8	80.9	80.9	80.9
Pump Suction - PSIA	6.47	5.84	5.09	4.89	5.10
Pump Flow -- lbs/min	1.87	1.58	.898	.596	.498
Dewar Pressure -- PSIA	25	20	20	20	20
Remarks					

DATA SUMMARY - Continued

Test Run	12	12	12	12	12
Date	1/12/61	1/12/61	2/5/62	2/5/62	2/5/62
Time at Equilibrium	2:00	3:15	12:10	12:42	1:05
H_2 Flow -- lbs/min	9 :83	7:85	149	213.5	258
GPM	16.5	13.18	250	358	433
P_1 -- PSIA	10.8	9.8	19.8	22.2	17.0
P_2 -- PSIA	6.3	6.0	12.8	15.2	13.2
P_s -- PSIA	5.83	5.73	10.28	11.74	11.25
T_1 -- ^oF	425.35	425.90	421.70	420.93	422.64
T_2 -- ^oF	428.20	428.40	424.33	423.28	424.15
T_s -- ^oF	428.53	428.60	425.65	424.85	425.10
ΔP -- Inches H_2O	-	-	2.4	4.0	Reverse Flow
ΔT_m	1.26	0.96	2.4	2.57	1.58
Q -- BTU/HR	-	-	54,180	69,200	54,250
U	11.3	10.35	86.7	103.6	132
Liquid Level %	80.9	80.9	90 to 95	90 to 95	90 to 95
Pump Suction - PSIA	4.97	4.75	9.28	10.76	10.66
Pump Flow -- lbs/min	.305	.214	4.72	6.04	4.59
Dewar Pressure -- PSIA	20	20	45	45	45
Remarks			512 RPM Shive on Pump Drive Motor		

DATA SUMMARY - Continued

Test Run	12	12	12	12	12
Date	2/5/62	2/4/62	2/4/62	2/4/62	2/4/62
Time at Equilibrium	4:38	4:48	-	5:04	5:15
H_2 Flow -- lbs/min	175.8	381.5	Reverse Flow	281.5	189.6
GPM	295	640	458	472	318
P_1 -- PSIA	20.2	-	-	-	-
P_2 -- PSIA	13.1	-	-	-	-
P_s -- PSIA	11.0	-	-	-	-
T_1 -- ^oF	421.60	-	-	-	-
T_2 -- ^oF	424.18	-	-	-	-
T_s -- ^oF	425.25	-	-	-	-
ΔP -- Inches H_2O	3.1	7.84	2.95	4.62	2.64
ΔT_m	2.1	-	-	-	-
Q -- BTU/HR	62,500	-	-	-	-
U	114	-	-	-	-
Liquid Level %	90 to 95	-	-	-	-
Pump Suction - PSIA	10.26	-	-	-	-
Pump Flow -- lbs/min	5.46	-	-	-	-
Dewar Pressure -- PSIA	45	-	-	-	-
Remarks	ΔP Determination Across H_2 Vapor Bulbs				

DATA SUMMARY - Continued

Test Run	12
Date	2/4/62
Time at Equilibrium	5:22
H_2 Flow -- lbs/min	63.6
GPM	106.8
P_1 -- PSIA	-
P_2 -- PSIA	-
P_s -- PSIA	-
T_1 -- ^oF	-
T_2 -- ^oF	-
T_s -- ^oF	-
ΔP -- Inches H_2O	1.156
ΔT_m	-
Q -- BTU/HR	-
U	-
Liquid Level %	-
Pump Suction - PSIA	-
Pump Flow -- lbs/min	-
Dewar Pressure -- PSIA	-
Remarks	ΔP Determination Across H_2 Vapor Bulbs.

APPENDIX 2

ILLUSTRATION SUMMARY

SUBCOOLER & COLD GAS VACUUM PUMP

APPENDIX 2

ILLUSTRATION SUMMARY

SUBCOOLER & COLD GAS PUMP

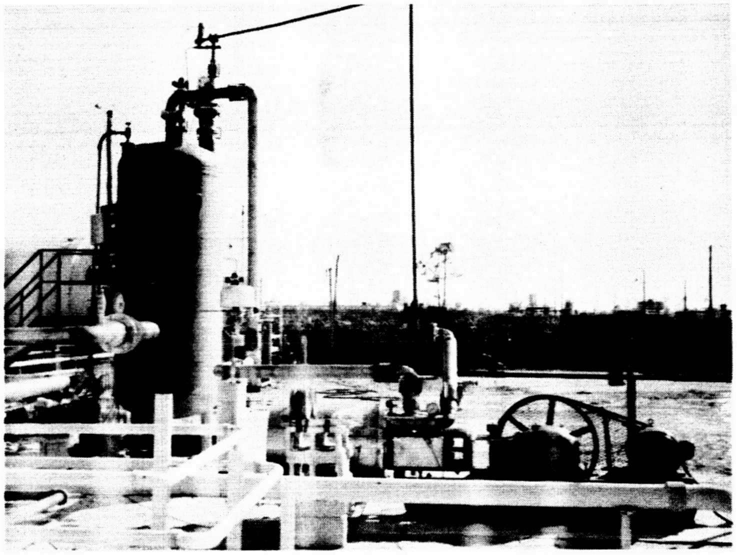


ILLUSTRATION 1 - SUBCOOLER & PUMP ASSEMBLY

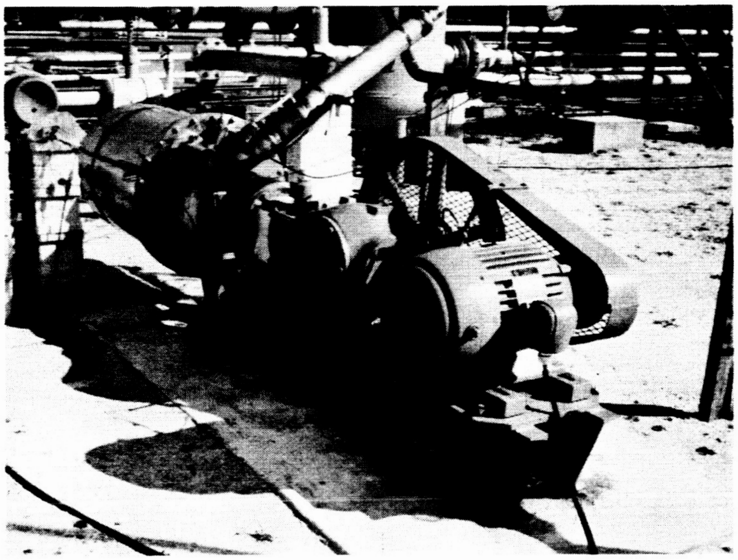


ILLUSTRATION 2 - COLD GAS VACUUM PUMP

VI Cold Gas Vacuum Pump

Introduction

This report covers the experiments performed on the cold gas vacuum pump, which will be used to generate the required low pressure over the boiling liquid hydrogen in the subcooler.

The purpose of the experiments was to obtain data to determine:

(1) Soundness of mechanical design.

(2) Performance data on horsepower requirements, head and capacity at the design point.

Vacuum Pump Design

Figure 17 shows a cross section of the pump. The pump is a double acting, one cylinder pump, driven by a 15 bhp electric motor. Most components of the pump are standard as known to the compressor and vacuum pump field. The cylinder with valves and insulation however, were built for the specific application of low temperature hydrogen gas pumping. Safety requirements are met through the use of a so-called distance piece, which is maintained under a nitrogen gas atmosphere and a hydrogen purge of the packing separating cylinder space and distance piece. With this arrangement it is impossible to draw air into the cylinder and generate explosive mixtures, either in the cylinder or in the discharge lines.

The gas is drawn into the cylinders through a vacuum jacketed line, two inch in diameter. The gas is discharged into the space around the cylinder and ducted away through a two inch line to a stack. Insulation is provided by a double walled, vacuum insulated bell-jar, which is bolted to a supporting steel plate. The plate in turn is insulated by means of four inches of polyurethane foam.

Test Apparatus

Tests on the pump were carried out in two phases. After completion of the assembly a cold nitrogen gas test was conducted to check the mechanical condition of the pump and its general behavior under moderate low temperature conditions. Figure 18 shows the schematics of the test diagram. As can be seen, the test apparatus was very simple. A major problem during the testing was the appearance of liquid droplets from time to time in the cylinder. Figure 15 shows the schematic flow arrangement of the subcooler and cold gas vacuum pump test. The test of vacuum pump and subcooler was combined for the following reasons:

(a) To simulate actual temperature conditions in the subcooler vacuum had to be generated in the subcooler.

N63-22161

AIR PRODUCTS AND CHEMICALS, INC.

ALLENTOWN, PENNSYLVANIA

Pa.

REPORT

OF

DEVELOPMENTAL TESTS

FOR THE

LIQUID HYDROGEN SERVICING SYSTEMS,

COMPLEX 37B, SATURN C-1

CAPE CANAVERAL, FLORIDA

Prepared For:

National Aeronautics and Space Administration

George C. Marshall Space Flight Center

Huntsville, Alabama

Prepared By:

R. E. Sotak

28 February 1962

Contract No. NAS8-1546

APCI ~~Project~~ No. 00-1-3140

104p

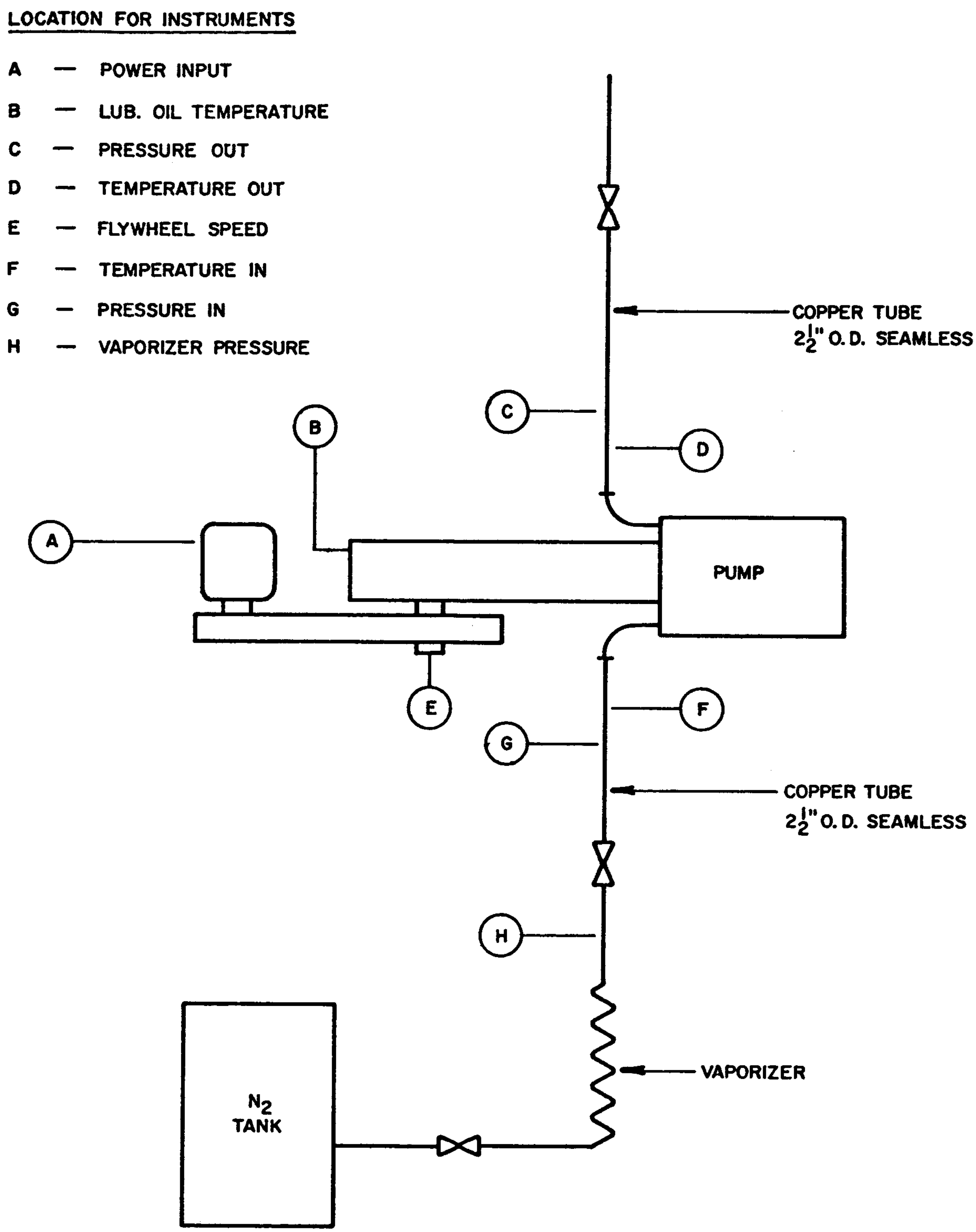
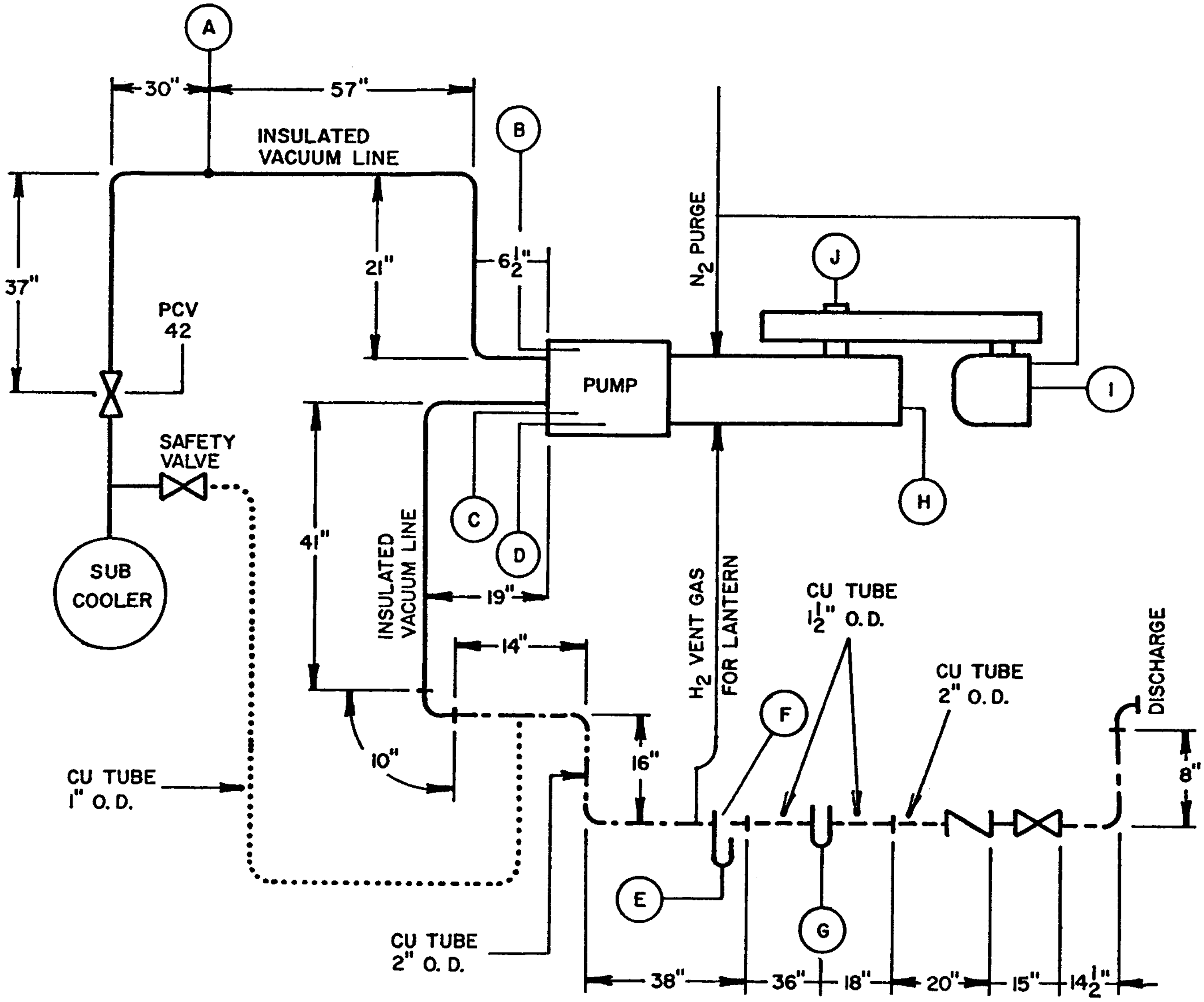


FIGURE 18
Test System – Part I – Vacuum Pump



LOCATION FOR INSTRUMENTS

A - PRESSURE IN
B - TEMPERATURE IN
C - TEMPERATURE OUT
D - CYLINDER WALL TEMPERATURE
E - PRESSURE OUT (ALSO ORIFICE PRESSURE)
F - TEMPERATURE ORIFICE
G - ORIFICE DIFFERENTIAL PRESSURE
H - LUBE OIL TEMPERATURE
I - POWER INPUT
J - FLYWHEEL SPEED

FIGURE 19

Test System - Part II - Vacuum Pump

(b) Time and cost of testing required the combination of as many separate tests as was possible.

(c) The performance of the pump perse was not of prime importance.

Figure 19 shows some detail of instrumentation used around the vacuum pump.

Discussion of Results

Nitrogen Gas Testing

Before operating the unit as a pump, friction in the frame and belt drive were determined by operating without cylinders and valves. The power required under these conditions was as follows:

Speed	K Watts	Horsepower
524 rpm	.625	.80
452 rpm	.625	.80
411 rpm	.575	.65
Electric Motor Idle	.350	

The friction of the complete unit was determined by operating without valves at ambient temperature. The unit was operated for 15 hours at 411 rpm. During this time the horsepower requirements dropped from 1.60 H.P. at the start to 1.25 H.P. at the end of the 15 hour period. The temperature of the outside of the cylinder at the center of the piston ring path was measured and found to vary between 117 and 57°F.

After insertion of the valves, the pump was operated for a total of 28 hours at 411 rpm pumping cold nitrogen gas.

A. The operation was satisfactory except when droplets of liquid nitrogen were drawn into the cylinder. The presence of liquid droplets was accompanied with loud knocking in the cylinder and the pump had to be shut down a number of times because of this.

B. The suction pressure was varied between 11.8 to 6.9 PSIA during long period runs. With the valve in the suction line shut, the suction pressure was 1.0 PSIA. The pump discharged to the atmosphere at 14.7 PSIA, except for short periods when the discharge pressure was increased to 24.7 PSIA.

C. The inlet gas temperature varied between plus 19 and minus 229°F. (Temperature was measured on the inlet pipe wall.) The discharge gas temperature varied from plus 80.6 to minus 112°F with an average increase of 130°F between inlet and outlet of the pump. The cylinder wall temperature was approximately the same as the discharge temperature during the entire test.

D. The power varied from 4.6 to 6.3 horsepower as the suction pressure was varied from 11.8 to 6.9 psia. The discharge pressure was maintained at a constant level of 14.7 psia.

E. The unit was operated at 520 rpm for a period of approximately one hour. The operation at this speed had to be discontinued because of poor control of the vaporizer. Liquid nitrogen entered the cylinder on many occasions and necessitated frequent shut downs of the machine.

After the nitrogen test, the vacuum pump cylinder was disassembled for inspection and shipment to the test site at West Palm Beach. Measurements of wear after 44 hours of operation are listed in the Appendix.

Hydrogen Gas Testing

The unit was assembled at the test site and installed in the subcooler test system in accordance with figure 15.

During the first test on hydrogen gas it was impossible to reach the required low temperature. The trouble was found to be a clearance problem of the valves, which was corrected.

A. Mechanical Performance

A total of 51 hours and 46 minutes of satisfactory operation pumping hydrogen gas at temperatures between -418°F and -424°F was logged during the test periods of January 4 to 13 and February 4 to 6, 1962.

Except for the difficulties experienced during the first attempt to pump hydrogen gas at -420°F, the pump operated very satisfactorily throughout the complete program. The pump was operated under the most severe conditions that it will probably ever encounter. It was cooled down from ambient to -420°F in less than 30 minutes and run for short periods, then stopped, kept cold for hours, and started again. A non-stop run of 26 hours and 56 minutes of excellent performance was logged January 11 and 12, 1962.

The evidence of liquid hydrogen at the outlet of the discharge line (23 feet of uninsulated copper pipe) a number of times indicates that the fluid going through the pump must have been in the two-phase region, (close to saturated liquid). A gradual increase in power input was observed before the liquid could be spotted at the discharge. Observing the pump, the increase in load was easily detected. Due to liquid in the space between the inside of the vacuum jacket and the outside of the foam insulation, the big flange also frosted rapidly. During normal operation, this pocket is filled with gas, and very little frosting is experienced. No typical liquid knocks in the cylinder were observed during any of these periods.

Liquid hydrogen in the pump was observed only at very high flow rates, (about 300 lb/hr.), and high liquid level in the subcooler.

B. Thermodynamic Performance

The first twenty hours of operation with hydrogen was in direct connection with subcooler tests during which only random data could be taken.

The performance data taken during the later performance runs for the vacuum pump lack reproducibility, because, due to the many variables in the complete test system, a perfect equilibrium was seldom obtained. This is especially evident at very low and very high flowrates.

1. Adiabatic and volumetric efficiency varies from around 20% to more than 100%. The low efficiencies both adiabatic and volumetric occur:

   a. Before the unit is completely cooled down, when the latent heat of the cylinder, valves, and piston unit causes a relatively big change in both suction and discharge temperature.

   b. When the unit is operated at a high compression ratio (2 and above). The friction load on the piston rings increases with increasing compression ratio which puts more heat into the gas stream.

   The low adiabatic efficiency in connection with high volumetric efficiency is mostly due to:

   a. An unbalanced system (not in thermodynamic equilibrium), where the latent heat is absorbed by the gas,

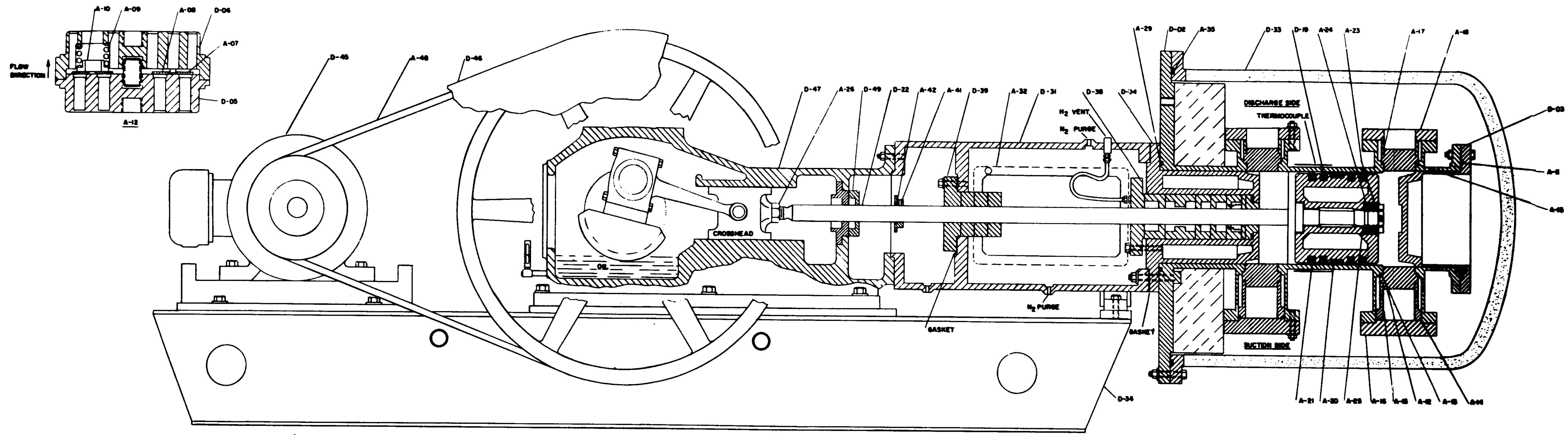
   b. Inaccuracy in measuring the outlet and orifice gas temperatures due to low sensitivity of thermocouples in this range.

   The high adiabatic and volumetric efficiency (95% and above) is caused by two-phase flow and inaccuracy in temperatures measurements. This occurs only when high boil-off rate in the subcooler is accompanied by a high liquid level. Liquid droplets in the gas will:

   a. Give erratic inlet temperature measurements.

   b. Give erratic outlet temperature measurements.

Air Products and Chemicals Inc.



D-02 Cylinder
D-03 Head End Cylinder Head
D-04 Frame End Cylinder Head
D-05 Valve Seat
D-06 Valve Stop Plate
A-07 Large Valve Plate
A-08 Small Valve Plate
A-09 Valve Spring
A-10 Valve Spring Retainer
A-11 Teflon-Coated Metal O-Ring

A-12 Suction and Discharge Valve
A-13 Teflon-Coated Metal O-Ring
A-14 Teflon O-Ring
A-15 Valve Retainer
A-16 Valve Cap
A-17 Valve Retainer
A-18 Valve Cap
D-19 Piston
A-20 Piston Rider Ring
A-21 Piston Ring

D-22 Piston Rod
A-23 Piston Rod Nut
A-24 Piston Rod Washer
A-25 Teflon O-Ring
A-26 Piston Rod Nut
A-29 Teflon-Coated Metal O-Ring
D-31 Distance Piece
A-32 Cover Plate
D-33 Vacuum Jacket
D-34 Base

A-35 Teflon O-Ring
D-38 Long Stuffing Box
D-39 Short Stuffing Box
A-41 Oil Slinger
A-42 Silicone Rubber O-Ring
D-45 Electric Motor
D-46 Flywheel and Belt Drive Guard
D-47 Frame
A-48 Belts
D-49 Wiper Box

Figure 17. Cold Gas Vacuum Pump

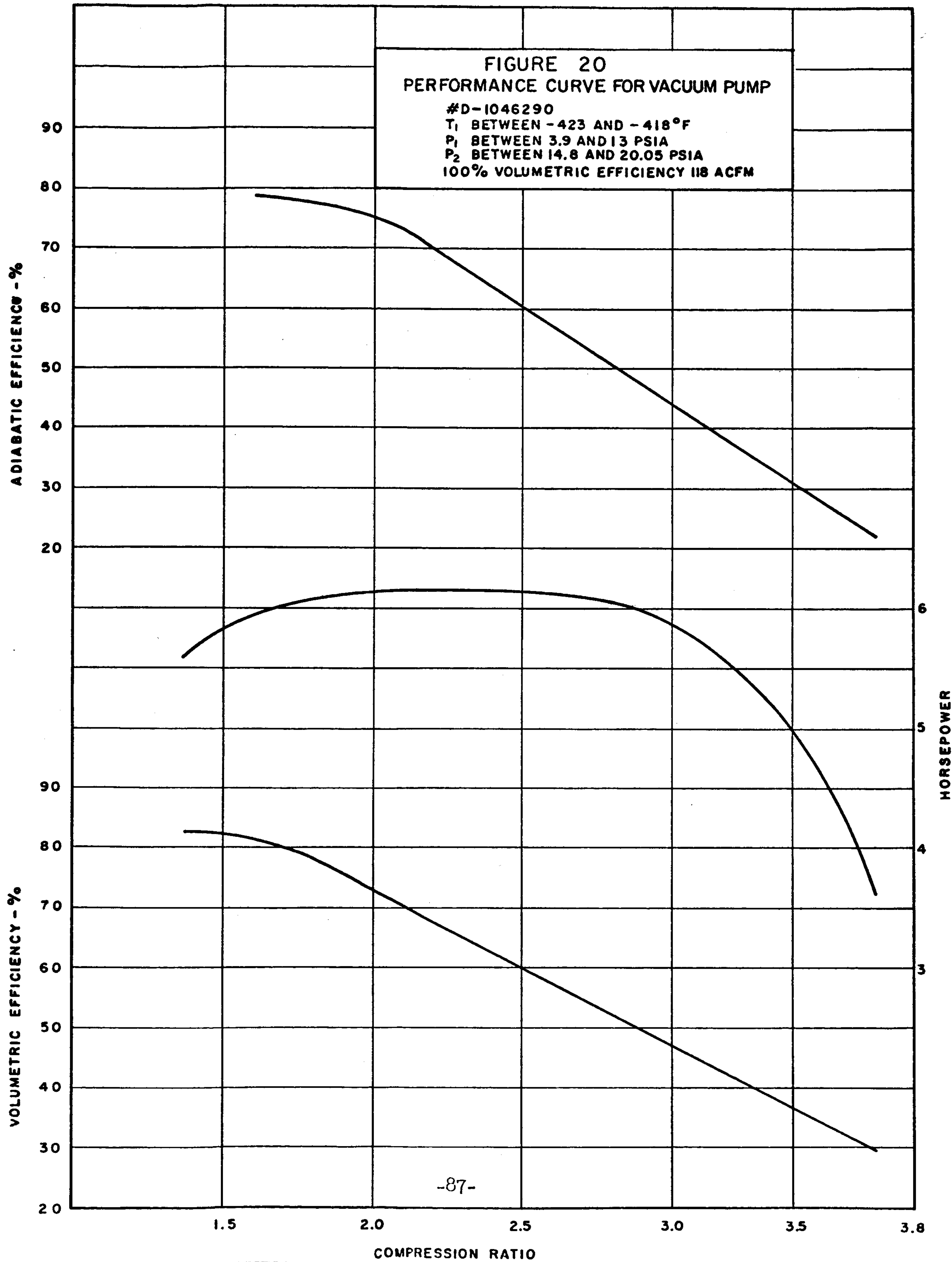


FIGURE 20
PERFORMANCE CURVE FOR VACUUM PUMP
#D-1046290
T_1 BETWEEN -423 AND -418°F
P_1 BETWEEN 3.9 AND 13 PSIA
P_2 BETWEEN 14.8 AND 20.05 PSIA
100% VOLUMETRIC EFFICIENCY 118 ACFM
ADIABATIC EFFICIENCY - %
VOLUMETRIC EFFICIENCY - %
HORSEPOWER
COMPRESSION RATIO
90
80
70
60
50
40
30
20
90
80
70
60
50
40
30
20
6
5
4
3
1.5
2.0
2.5
3.0
3.5
3.8


FIGURE 21
PERFORMANCE RUN
GRAPH I
H.P.
HORSEPOWER
R = COMP. RATIO
COMP. RATIO
VOL. EFF.
Pin
SUCTION PRESSURE, PSIA
90%
80%
70%
60%
50%
40%
30%
TEMP °F
TCYL.
TOUT
START PUMP AT 3:13 P.M. 1-11-62
TRANSFER TO "D" TANK AT 6:15 P.M. 1-11-62
3:P.M. 1-11-62
4:P.M. 1-11-62
5:P.M. 1-11-62
6:P.M. 1-11-62
TIME

FIGURE 22
ENDURENCE RUN
GRAPH II
H.P.
R = COMP. RATIO
Pin
VOL. EFF.
TCYL
TOUT
"C" TO "D" TRANSFER AT 7 A.M. 1-12-62
HORSEPOWER
COMP. RATIO
SUCTION PRESSURE, PSIA
TEMP., °F
VOL. EFF.
90%
80%
70%
60%
50%
40%
30%
12
10
8
6
4
2
4
3
2
1
14
12
10
8
6
4
2
0
440
0
-40
-80
-120
-160
-200
-240
-280
-320
-360
-400
-440
6:30 P.M. 1-11-62
9:30 P.M. 1-11-62
12:30 P.M. 1-12-62
TIME
6:30 A.M. 1-12-62
10:30 A.M. 1-12-62
2:30 P.M. 1-12-62

FIGURE 23
PERFORMANCE RUN
GRAPH III
H.P.
R= COMP. RATIO
Pin
VOL. EFF.
TCYL
TOUT
START PERFORMANCE RUM AT 3:0 P.M. 1-12-62
END PERFORMANCE AT 4:41 P.M. 1-12-62
VOL. EFF.
90%
80%
70%
60%
50%
40%
COMP. RATIO
SUCTION PRESSURE PSIA
TEMP., °F
12
10
8
6
4
2
4
3
2
1
14
12
10
8
6
4
2
0
+40
0
-40
-80
-120
-160
-200
-240
-280
-320
-360
-400
-440
3:P.M. 1-12-62
4:P.M. 1-12-62
5:P.M. 1-12-62
6:P.M. 1-12-62
TIME

c. Vaporize in the cylinder, causing an increase of the gas volume and a cooling of the gas. (Latent heat of liquid hydrogen).

d. Give erratic orifice temperature and differential pressure if the droplets are not completely vaporized by the time the fluid reaches the orifice.

2. Warm up of gas from the shell-side of the subcooler to the inlet of the pump.

   This is caused by heat leak into the gas stream in the transfer line and in the pump, especially from the discharge gas that surrounds the inlet manifold.

3. Difference in pump flowrate and boil-off rate in the subcooler is due to:

   a. Delay between the two measurements when transferring liquid from Tank D to C. The subcooler boil-off will be slightly ahead of the pump flowrates, because the weight measurements for the subcooler flow are made at the D tank which is 120 feet away from the subcooler. This means that the actual boil-off in the subcooler comes after the new liquid flowrate is established.

   b. The subcooler boil-off rate does not include boil-off due to heat leak into the subcooler nor does it account for the liquid leaving the shell-side on high boil-off rate and high liquid level.

Blank-Off Point

Pump Speed	Hydrogen Gas Ambient Temperature	Hydrogen Gas at -420°F
412 RPM	.5 psia	.5 psia
510 RPM	.5 psia	

Blank-off pressure for cold hydrogen gas at 510 RPM was not obtained due to a leaking valve (PCV-42) in the suction line. The lowest suction pressure measured at this speed and temperature was 2.0 psia, and at this suction pressure, enough cold gas was being pumped to keep the cylinder wall at -100°F thirty minutes after PCV-42 was shut. Discharge pressure was 14.8 psia during all tests.

C. Performance Curve

The performance curve was obtained by taking the average of a number of readings (see Data for Performance Curve).

The performance curve shows that:

1. The adiabatic and volumetric efficiencies increase with decreasing compression ratio. This agrees with the theoretical curves, except the measured efficiencies drop off too fast with higher compression ratios. This is mostly due to the added friction load at the higher compression ratios.

2. The horsepower curve shows good relationship to the theoretical curve. The theoretical horsepower curve has a maximum of 5.6 HP at a compression ratio of 2.35 and tapers off evenly both ways decreasing horsepower with increasing and decreasing pressure ratio. The performance curve shows about 6.40 HP at a compression ratio of 2.35. This gives .80 HP friction which compares favorably with .65 HP, the measured friction.

Design Point

Design Criteria:

Inlet Pressure: 8.5 psia
Temperature: -426.0°F
Outlet Pressure: 16.0 psia
Suction Flow Rate: 98.6 psia

Data from the Performance Curve:

At Compression Ratio: $\frac{16.0}{8.5} = \underline{\underline{1.88}}$

Operating Speed: 412 RPM
Volumetric Efficiency: 76%
Power Input: $\underline{\underline{6.2 \text{ HP}}}$
Suction Flow Rate:
118 x 76 = $\underline{\underline{89.7 \text{ ACFM}}}$

This is somewhat lower than the design criteria. However, much higher flow rates for the same compression ratio were experienced a number of times, during the test program. (see Data for Performance Curve).

While this lack of equilibrium conditions handicapped the evaluation of exact thermodynamic performance parameters, it must be remembered that the pump, in its normal mission, will operate for short periods more often than long periods. These tests have demonstrated that it meets its performance requirements.

APPENDIX

DISASSEMBLING AND INSPECTION AFTER COMPLETED TESTING

DISASSEMBLING OF VACUUM PUMP

After testing ended at West Palm Beach, the complete unit was transferred to the maintenance shop for disassembling and inspection.

Inspection

Vacuum Jacket

A thin layer of black dust (wear off from the carbon filled piston rings) coated the inside, otherwise no changes were observed.

Insulation

Insulation on the Big Flange (ISO-FOAM) had 5 - 6 radial cracks, from the outside diameter of the cylinder to the outer edge of the insulation. The cracks were about 1/64" to 1/32" wide.

Valves

Teflon O-rings on suction side showed no evidence of leakage.

Teflon coated metal O-rings on suction and discharge sides also showed no evidence of leakage.

Valve plates were wearing in evenly.

Valve seats were wearing in evenly.

Suction and discharge valves, in general, showed no evidence of malfunctioning.

Cylinder Bore

Surface finish was very good.

Measurements - See Measurement Data.

Piston and Piston Rod Assembly

Rod - No visible wear.

Piston - No visible or measurable wear of ring grooves.

Piston rider ring - wearing in evenly.

Piston rings - wearing in evenly.

Piston Rod Stuffing Box - Long

Segmental rings are not yet worn in, but are wearing in evenly.

Piston Rod Stuffing Box - Short

Segmental rings are wearing in evenly.

Piston Rod - Wiper Rings

Visible wear - see discussion of results.

Frame

No visible wear was evident on any part.

Belts and Sheaves

No visible wear.

Assembly

The unit was completely assembled according to NASA Drawing No. D-10462950 and made ready for shipping to Cape Canaveral.

Measurements

Measurements were taken during original assembly, after 44 hours operation pumping cold nitrogen gas, and after 52 hours operation pumping cold hydrogen gas.

Dimensions were checked on the:

Cylinder Bore
Piston Rod
Piston Rider Ring
Piston Rings
Bore in Valve Pockets (adjacent to the Cylinder Bore)

DISCUSSION OF DISASSEMBLING AND INSPECTION RESULTS

Vacuum Jacket

The black dust deposit on the inside wall is "wear off" from the carbon filled teflon piston rings. This deposit will decrease as the rings wear in.

Insulation

The decrease in insulation properties should be negligible. No excessive "frosting" of the big flange was experienced except when liquid hydrogen reached the insulation space behind the flange. Liquid entered the pump when experimenting and adjusting LCV-9 and will not occur during normal operation of the system.

Valves

Inspection showed that the valves were giving good mechanical performance with negligible wear. Expected life: 3,000 hours.

Cylinder Bore and Valve Pockets

Surface finish was better than expected. The measurements show the cylinder bore to be from .0015 inches to .0045 inches out of round. This is very little considering the rapid and uneven "cool downs" it was subject to.

Piston and Piston Rod Assembly

Rod - Measurements show no measurable wear, indicating that carbon filled teflon rubbing on annealed 304 stainless steel gives good wear conditions, both for the steel and the teflon (see Stuffing Boxes).

Piston - The only parts of the piston (aluminum) subject to wear are the ring grooves, especially where the compression rings (stainless steel) are located. However, no wear of the grooves was detected.

Piston Rider Ring - A total wear of .0015 inch radially was measured after 96 hours of operation. This should give the ring at least 2,300 hours service. The wear rate, however, is expected to decrease with hours of operation. As the cylinder bore gets coated with teflon, rubbed off the rings, the friction decreases. In other words, teflon rubs on teflon with a very small coefficient of friction. The second ring should give an appreciable increase in service life. No measurable wear on the width.

Piston Rings - Maximum measured wear on any of four rings was .002 inch which should give a service life in excess of 3,000 hours. Improvement of this number is very likely, see "5 c".

No measurable wear on the width.

Piston Rod Stuffing Boxes - Long and Short

The segmental rings show less wear than expected. The rings in the short stuffing box (warm end, ambient or slightly above) were worn in more than the rings in the long box (temperature range 420°F to 50°F). This indicates that the friction is higher at ambient than at cryogenic temperatures.

Piston Rod - Wiper Rings

These rings (Babbit) show visible wear, which was expected, since Babbit rings are used in order to save the piston rod, annealed 304 stainless steel. Expected life should be 2,000 hours.

Frame, Belts, and Sheaves

These parts are fairly lightly loaded under normal operating conditions and no appreciable wear is expected. If operated with liquid hydrogen in the cylinder, shock and overload might cause permanent damage to the bearings and the belts.

General

The complete assembly was in excellent condition despite the fact that several tests were run to the extreme of passing liquid hydrogen through the pump as evidenced by pulsating and two-phase flow from the pump discharge line.

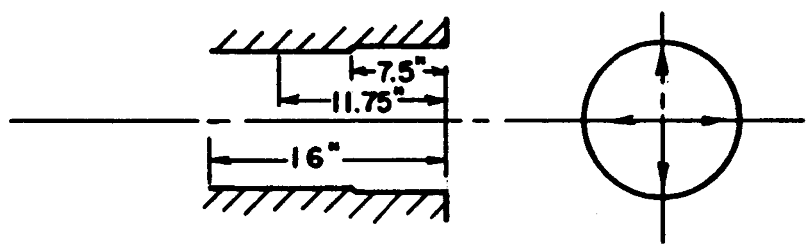
COLD GAS VACUUM PUMP INSPECTION

Dimensions to check every time the pieces are disassembled.

Cylinder D-10462902

Cylinder Bore Piston Ring Section.

Horizontal	New	44 Hours Operation	96 Hours Operation
7.5" from Head End	8.002	8.0030	8.0025
11.750" from Head End	8.0013	8.0026	8.002
16.0" from Head End	8.0019	8.0036	8.003
Vertical			
7.5" from Head End	8.0015	8.0011	8.001
11.75" from Head End	8.0005	7.9998	7.999
16.0" from Head End	8.0003	7.9994	7.9985

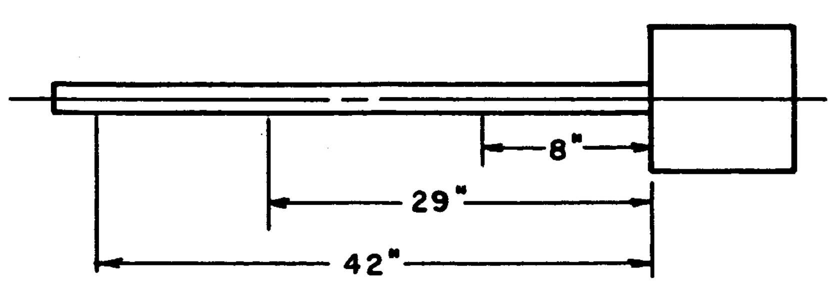


Piston and Piston Rod Assembly D-10462927

When taking this Assembly out, mark vertical centerline the way it has been operating.

Diameter

Horizontal - 8" from the Piston	1.3741	1.3741	1.374
Vertical - 8" from the Piston	1.3741	1.3741	1.374
Horizontal - 29" from the Piston	1.3743	1.3743	1.3743
Vertical - 29" from the Piston	1.3743	1.3743	1.374
Horizontal - 42" from the Piston	1.3741	1.3740	1.3742
Vertical - 42" from the Piston	1.3739	1.3739	1.3742



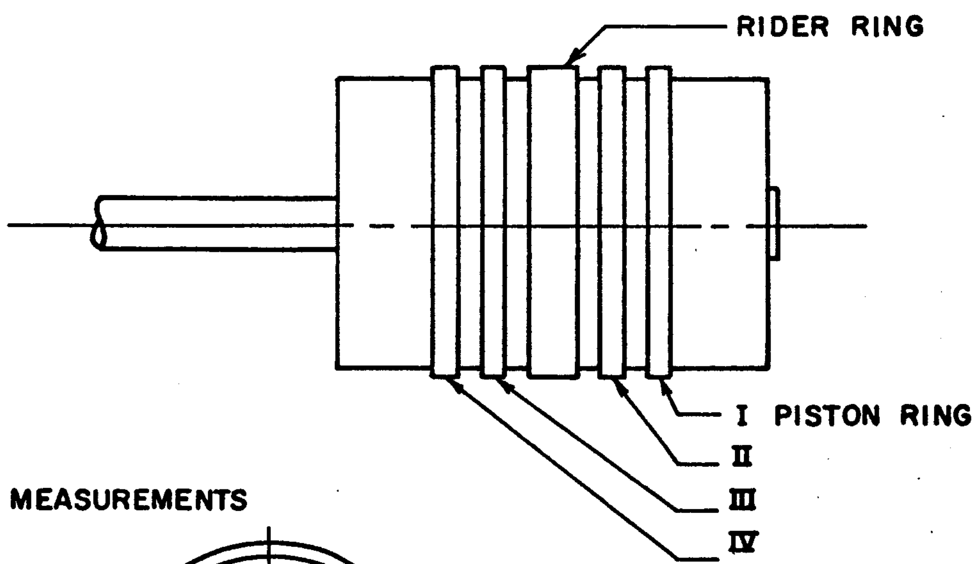
COLD GAS VACUUM PUMP INSPECTION

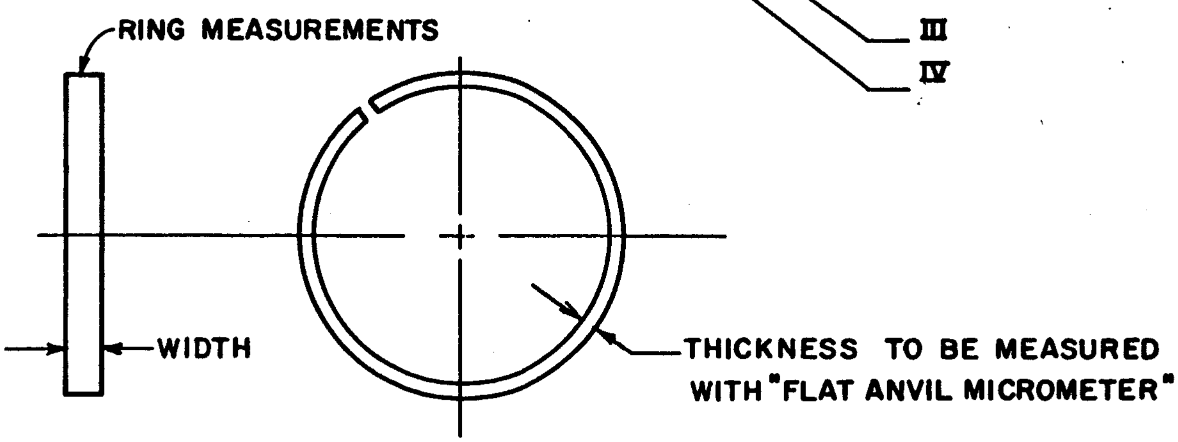
Piston Rider Ring H-10462920

		New	44 Hours Operation	96 Hours Operation
Min. thickness of Ring		.379	.378	.3775
Min. thickness Allowed:	.0350 In.			
Width of Ring:	Max.	.997	.997	.997
	Min.	.9965	.996	.996

Piston Ring A-10462921

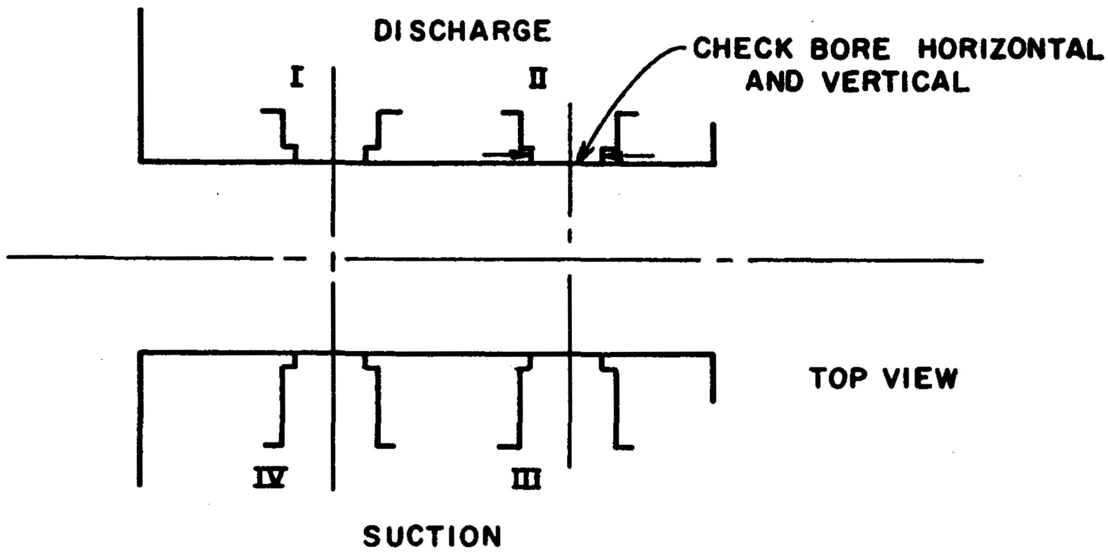
		New	44 Hours Operation	96 Hours Operation
I.	Min. thickness of Ring	.3785	.377	.3765
	Width	.4335	.434	.4335
II.	Min. thickness	.378	.377	.377
	Width	.433	.433	.4335
III.	Min. thickness	.3775	.376	.3765
	Width	.4335	.434	.4335
IV.	Min. thickness	.378	.3775	.3775
	Width	.4265	.4275	.433





COLD GAS VACUUM PUMP INSPECTION

Bore in Valve Pockets



		New	44 Hours Operation	96 Hours Operation
I.	Horizontal	3.019	3.020	3.0195
	Vertical	3.007	3.007	3.009
II.	Horizontal	3.020	3.021	3.020
	Vertical	3.008	3.009	3.009
III.	Horizontal	3.009	3.009	3.008
	Vertical	3.007	3.006	3.0065
IV.	Horizontal	3.014	3.014	3.0145
	Vertical	3.013	3.013	3.012

DATA FOR PERFORMANCE CURVE

These data are collected randomly throughout the Test Program.
Pump Speed - 412 rpm
100% Volumetric Efficiency - 118 ACFM

	Compression Ratio	Pressure In	Pressure Out	Adiabatic Efficiency	Volumetric Efficiency	Horsepower
	1.46	10.8	15.8	38.9	83.3	5.35
	1.36	11.8	16.0	100	80.7	5.3
	1.48	10.6	15.7	100	88.2	5.35
	1.37	11.8	16.2	31.6	74.4	5.45
	1.3	12.5	16.2		69.7	4.8
	1.2	9.6	19.7	100+	99.5	7.0
	1.36	11.8	16.0	100	80.9	5.4
	1.37	11.8	16.2	100	82.9	5.25
	1.44	13.8	19.8	58.5	82.8	6.3
	1.49	10.6	15.8	64.6	78.3	5.3
Average	1.38	11.51	16.74	77.0	82.07	5.6
	1.50	9.6	17.8	100	101.5	6.35
	1.62	9.8	15.9	44.2	80.7	5.7
	1.62	9.6	15.5	70.8	64.2	5.5
	1.81	8.5	15.4	100	77.3	5.6
	1.90	8.1	15.4	11.0	71.7	5.2
	1.82	10.7	19.5	100	81.4	6.93
	1.79	11.0	19.7	100	77.7	7.05
	1.80	9.6	17.8	100	99.5	6.4
	1.90	10.30	19.6	100	75.9	6.85
	1.85	8.1	15.0	67	56	5.35
Average	1.761	9.53	17.16	79.30	78.59	6.093
	2.00	9.6	16.4	100	101	6.05
	2.13	7.0	14.9	47	33.2	5.85
	2.06	7.4	15.2	51.4	69.9	5.60
	2.06	7.4	15.2	42.5	61.2	5.45
	2.04	9.8	19.95	100	77.5	6.80
	2.03	7.6	15.4	86.3	76.3	5.83
	2.35	8.3	19.5	71.5	75.4	7.05
	2.42	7.4	17.9	100	68	6.6
	2.11	9.3	19.6	90.7	68.9	6.75
	2.35	6.4	15.0	26.1	47.5	5.40
Average	2.155	8.02	16.9	71.55	67.89	6.138

	Compression Ratio	Pressure In	Pressure Out	Adiabatic Efficiency	Volumetric Efficiency	Horsepower
	2.50	6.4	15.0	53.2	56.9	5.70
	2.53	7.1	17.95	100	68.8	6.58
	2.59	6.9	17.9	100	64.9	6.50
	2.54	7.9	20.05	48.4	55.5	6.75
	2.69	5.5	14.8	29.5	40.4	5.75
	2.82	7.1	20.05	38.3	47.8	6.75
	2.89	6.9	19.95	35.1	47.2	5.58
	2.96	5.0	14.8	24.1	38.2	5.37
	2.96	5.0	14.8	37.7	43	5.68
	2.92	5.1	14.9	37.2	50.2	5.48
Average	2.74	6.29	17.02	50.35	51.29	6.014
	3.00	5.4	16.2	41.9	50.2	5.97
	3.10	4.8	14.9	28.8	43.0	5.58
	3.12	5.2	16.2	46.8	51.5	5.95
	3.02	4.9	14.8	24.2	36.8	5.75
	3.08	4.8	14.8	21.9	38.8	5.45
	3.35	5.9	19.75	24.6	38.6	6.35
	3.05	4.9	14.9	30.6	33.1	5.30
	3.02	4.9	14.8	35.8	47.9	5.45
	3.27	4.9	16.0	46.8	52.8	5.95
	3.37	4.4	14.8	20.8	46.0	5.45
Average	3.138	5.01	15.715	32.22	43.87	5.72
Single Point	3.67	5.4	19.8	22.40	29.60	3.63